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ELECTRIC BRIGHT ANNEALING OF MILD STRIP

A battery of sixteen bright annealing furnaces at the Courtybella Works of the Whitehead Iron & Steel Co., Ltd., Newport. The loading ranges from 110 kW to 130 kW per furnace, giving an output of 1,000 tons of steel strip a week.

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Electronics: Their Scope in Heavy Engineering

By W. G. THOMPSON, Ph.D., B.Sc., M.I.E.E.,

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This paper, presented before the North East Coast Institution of Engineers and Shipbuilders, in Newcastle-on-Tyne, on the 17th December, 1945, and reproduced, by kind permission, from the Institution Transactions, Vol. 62, is a survey of the various types of electronic equipment and their uses in the engineering field. The first part of the paper deals with electronic devices proper, including valves, mercury vapour and other apparatus. The difference between vacuum and vapour devices is explained with reference to their control and functions.

Part II of the paper shows the application of electronic devices in engineering, and their use in research, manufacture, testing and power control.

The technical and economic aspects of such applications are also discussed.

PART I. ELECTRONICS.

1. INTRODUCTION.

A GLANCE at the history of engineering developments during the past hundred years shows a steady infiltration of electrical methods into the field of mechanical engineering, a convergence of the mechanical and electrical sciences and the influence of progress of one branch upon the other. There is also the incidence of significant discoveries leading to the construction of new machines and altered trends of development. Amongst such discoveries in the last fifty years are Thomson's researches proving the quantum nature of the conduction of electricity *in vacuo* or low-pressure gases by electrons, Fleming's application of the Edison effect in the invention of the thermionic valve, and Cooper-Hewitt's development of the mercury-arc rectifier from the mercury-vapour discharge lamp. It, is however, only in the last few years that the fundamental identity of the widely different applications of electrical discharge phenomena in the various branches of engineering has become generally recognized. Evidence of this recognition is provided by the use of the word "electronics" as a generic term covering the study and application of devices embodying the conduction of electricity by free electrons *in vacuo* or by electrons and charged atoms, *i.e.*, ions, in low-pressure vapour spaces.

The successful application of electronics to engineering depends upon the effective combination of the techniques of the light current and heavy industries. This paper is an attempt to appraise the possibilities and the limitations of such a combination, by first giving the electronic background and later filling in some of the engineering details.

2. ELECTRONIC DEVICES.

The chart shown as Table 1 indicates the wide range of apparatus covered by the words "electronic devices." This range includes small and large high-vacuum valves of the radio type and mercury-arc rectifiers for large powers, as well as a number of other variants such as the photo-electric cell, the cathode-ray oscillograph, the X-ray tube and the gas discharge lamp. The fundamental construction of all these devices is the same; it is that of an outer vacuum-tight vessel of glass or metal into which electrical connections are introduced through vacuum seals and insulating bushings. As there is an internal dissipation of energy during operation suitable ventilated housings or, if necessary, forced cooling has to be provided. Within the vessel are arranged an electron emitting surface known as the cathode and an electron collecting surface called the anode. The cathode may take several forms such as a tungsten wire heated to incandescence, or a tubular surface coated with an alkaline earth and having an internal and insulated heating element, or again a mercury pool cathode is used from which electrons are emitted at the footpoints of an arc discharge. Variants in the forms of anodes

are rolled metal cylinders or pressings, machined graphite blocks or machined copper parts arranged to form part of the vacuum-tight envelope.

Additional electrodes in the form of grids may be interposed between the cathode and the anode to control the flow of electrons from the cathode. The grid constructions range from fine wire meshes or metal strips to perforated graphite plates according to the type of electronic device to which they are fitted.

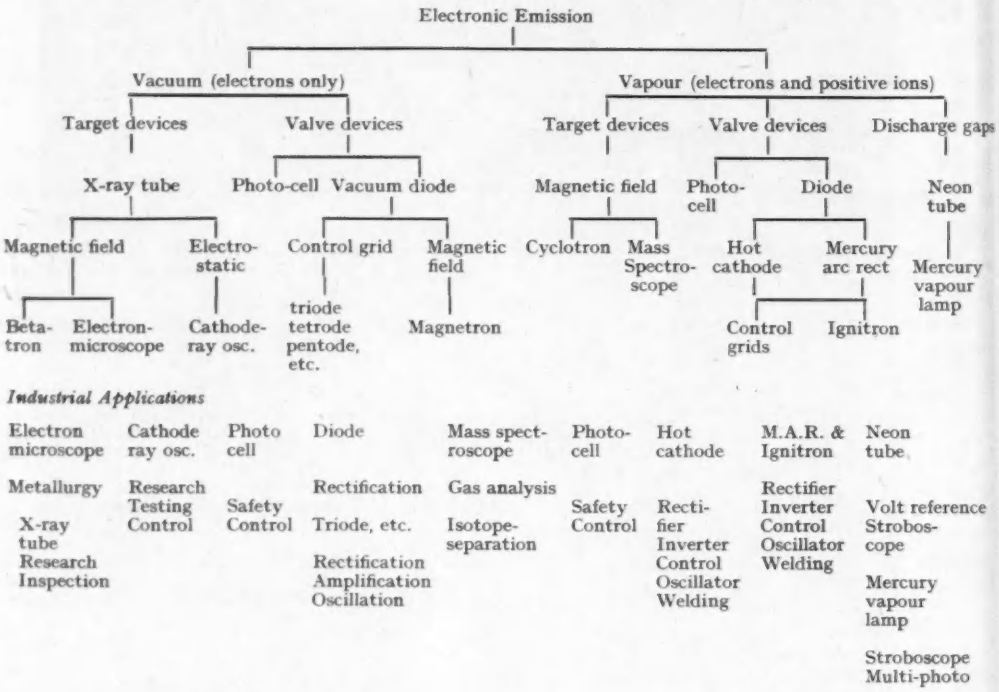
Conduction in these devices is characterized by the facts that the positive ions move in the same direction as the current, the negative electrons in the reverse direction.

(*a*) *Valves and their characteristics.*

Valves form the most numerous group of electronic devices and to illustrate their different classes fig. 1 has been prepared showing the analogy between the electrical types and their counterparts in a hydraulic circuit. The thermionic or vacuum diode represents the simplest type of rectifying or non-return valve. It is suitable for small currents of the order of milli-amperes, but if necessary can be built for very high electrical pressures, *i.e.*, 200,000 volts, and a small-bore non-return valve provides a useful analogy. Now in a thermionic valve the conduction is entirely electronic and if a grid be introduced the current flow can be regulated smoothly and continuously by the amount of negative bias applied to the grid, though of course the non-return feature is still present. This valve can be represented by a needle valve in which the "lift" is regulated by an opposing adjustable compression spring as in fig. 1*b*. In vacuum valves either in A.C. or D.C. circuits the current flow can be continuously varied or even cut off by the grid, hence the valves function as "modulators" and are equivalent to variable high resistances in the circuit.

If a gas such as argon or mercury vapour be present the character of the conduction in the valve is entirely changed. In the first place both negative electrons and positive ions produced by collisions of these charges with neutral molecules contribute to the current flow. The discharge is of the low-

TABLE 1.



resistance type limited in current only by the conditions in the external circuit. Thus a vapour diode is analogous to an ordinary "clack" valve of wide bore. (Fig. 1*c*). The introduction of a grid negative bias into a vapour valve provides a means of inhibiting the flow of current, but once this is released by making the grid momentarily positive, the valve loses the ability to control the flow of current until it is reduced to zero by external means. Such a device can be represented by a latched non-return valve, fig. 1*d*, where the latching can only be restored by stopping the flow. The vapour-filled valves are therefore not "modulators" but merely "triggers." Table 2 is a list of the devices with the "latched" characteristic.

Valve Characteristics.

Fig. 2 shows the characteristic curves of the high-vacuum triode explained in terms of the operation of a hydraulic valve, the sloping lines representing the flow through the valve for variable "lifts" at constant pressure difference. If there is a pressure drop due to resistance in the supply line then the dynamic characteristic is appropriate for the working conditions. Table 3 shows the derivation of the various factors used in valve calculations.

The valve characteristics may be modified by the addition of more grids between the anode and the cathode. One additional grid produces the tetrode, with amplification factors up to 1000, but with a "kink" in the characteristic at low voltages. This can be overcome by a third grid, the valve then being known as the pentode.

No similar characteristics exist in the

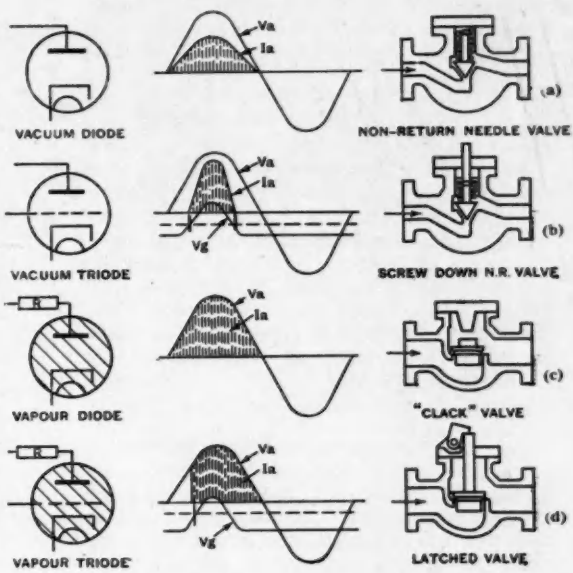


Fig. 1.—Comparison between electronic and hydraulic valves.

TABLE 2.

Type	Remarks
Hot-cathode Gas-filled	Mean current about 0·5 amp. Reverse voltage limit about 400 volts. Small heater current. Not temperature sensitive. Grid control current—few milliamperes.
Hot-cathode Mercury vapour	Made in sizes up to about 10 amps. mean current. Reverse voltage limits up to 1000 according to size. Heavier heater current. Temperature sensitive. Grid control current—few milliamperes.
Mercury Arc : (*a*) Glass bulb multi-anode	Sizes range from 10 to 400 amps. Reverse voltage limits up to 30,000 according to design. Auxiliary anodes maintain cathode spot on light load. Ignition device for starting. Cooling fan speed controlled. Grid control current less than 0·5 amp.
(*b*) Steel tank, pumpless, air cooled, multi-anode	Sizes from 100 to over 1,000 amps. Reverse voltage limits up to 50,000 according to design. Auxiliaries similar to glass bulb. Constant speed fan. Grid control current less than 1 amp.
Single anode Ignitron type	Sizes range from few amperes to 800 amps. per cylinder. Reverse voltage limits up to 20,000 according to design. Water or air cooling. Igniter current up to 30 amps. peak. Grid control provided by igniter, but control grids also sometimes used.

mercury-vapour group (see fig. 3) and with a D.C. supply the valves are "full on" immediately the grids are released. With an A.C.

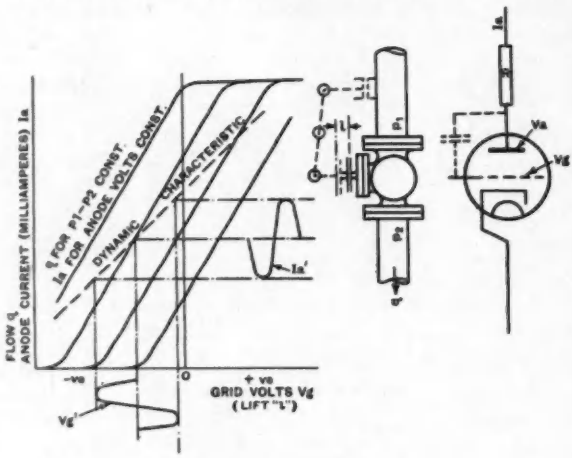


Fig. 2.—Analogy for valve characteristics.

supply to the anode the grids can be released in synchronism with the supply voltage at each positive half cycle, and by adjusting the phase of the triggering impulses a corresponding change in the mean D.C. voltage output can be produced. The resultant voltage is given by $E_g = E_o \cos \alpha$ where E_o is the uncontrolled voltage and α the angle of retard of the ignition impulses. Fig. 4*a* illustrates a mechanical method of obtaining a phase shift of the grid impulses with respect to the supply voltage using a combination of mechanical displacement and rotating magnetic field to give a differential effect. The electrical phase displacement is related to the mechanical movement by $\phi el = \phi$mech.$/p$, where p is the number of pairs of poles in the windings. A purely static means of carrying out the same operation by means of a phase-shifting network including resistances and saturable reactors is shown in fig. 4*b*. Although mercury-vapour valves can be controlled by sinusoidal wave forms, peaky voltage or steep fronted grid impulses derived from valve or magnetic saturation circuits are desirable for precision in operation.

To sum up: Vacuum valves are responsive to both grid voltage variation and phase shift; vapour valves are controllable over a range by phase shifting grid impulses of sufficient magnitude. These principles govern the operation of all electronic control systems.

(*b*) *Target, deflection and other devices.*

There is a variety of electronic devices of considerable interest and application whose mechanism depends upon the deflection of an electron beam focused upon a target, and details of these are given in Table 4 corresponding to fig. 5.

There is in addition a number of other devices such as the photo-electric cell, which releases electrons under the incidence of light waves; the "magic eye" giving visual indication of balanced voltages in the form of a triangular shadow on a target; neon lamps operating as voltage limiters or alternatively providing constant reference voltages; vapour discharge lamps providing sources of instantaneous illumination for stroboscopy or multiple-flash photography.

TABLE 3.

Factor	Definition	Electrical	Hydraulic
Amplification factor	Change in pressure across valve/Change in "lift" with flow constant.	$\frac{dV_a}{dVg}$ I const.	$\frac{d(p_1-p_2)}{dl}$ q const.
Impedance	Change in pressure/Change in flow with "lift" constant.	$\frac{dV_a}{dI}$ V_g const.	$\frac{d(p_1-p_2)}{dq}$ l const.
Conductance	Change in flow/Change in "lift," pressure constant.	$\frac{dI}{dV_g}$ V_a const.	$\frac{dq}{dl}$ p_1-p_2 const.

3. NON-VACUUM ELEMENTS.

The non-vacuum elements in electronic

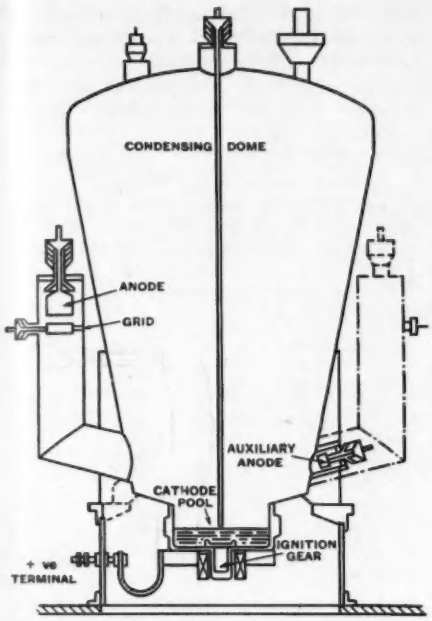


Fig. 3.—Sectional view of steel tank, pumpless, air cooled mercury arc rectifier.

work comprise the usual array of transformers, chokes, condensers and resistances. In addition there may be metal-oxide rectifiers, electromagnetic relays and protective elements such as fuses. They are usually the most numerous and not the least expensive components in the circuit. Apart from their usual functions these components are used for phase multiplication, energy storage, time delay, integrating and differentiating, resonant and oscillatory circuits, surge absorbing, etc.

4. GENERAL CONSIDERATION OF ELECTRONIC CIRCUITS.

A feature of the electronic circuit not always appreciated is the number of ordinary components necessary in addition to the electronic devices. More obvious, but again deceptive is the complication of the circuits, particularly in view of the general practice of omitting heater circuits and auxiliaries from diagrams and representing polyphase by single-phase circuits. Fortunately most of these difficulties are diminished if the following principles are remembered :—first, electronic devices usually contain no inherent source of electrical power and therefore a direct or alternating current supply is required to operate the circuit. Secondly, electronic devices controlled by electrostatic screens or grids are voltage devices and therefore require a source of potential but practically no power in their control circuits. Thirdly, there are auxiliary circuits to provide filament heating or some equivalent means for the liberation of electrons inside the device. It is thus possible to trace the various paths of energy flow in a circuit

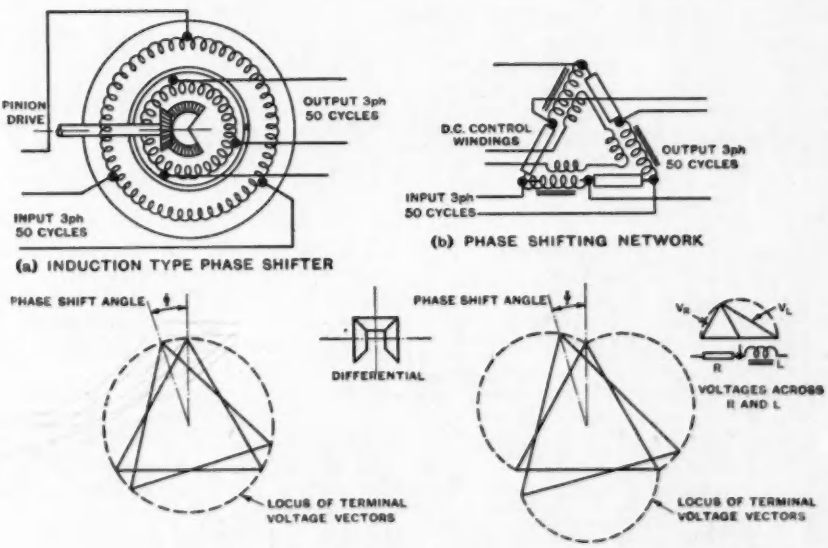


Fig. 4.—(*a*) Mechanical and (*b*) Static methods of phase shifting.

and identify the functions of the different components according to whether they are part of the power circuit, the control circuit, or the auxiliary circuits.

Danger or faulty operation signals must take precedence over purely operational signals whether manual or automatic.

Whatever the type of apparatus and whatever the object of control these essential features must be present and indeed many of the requirements are so similar even for widely different electronic applications that the same type of control unit can serve for several kinds of apparatus.

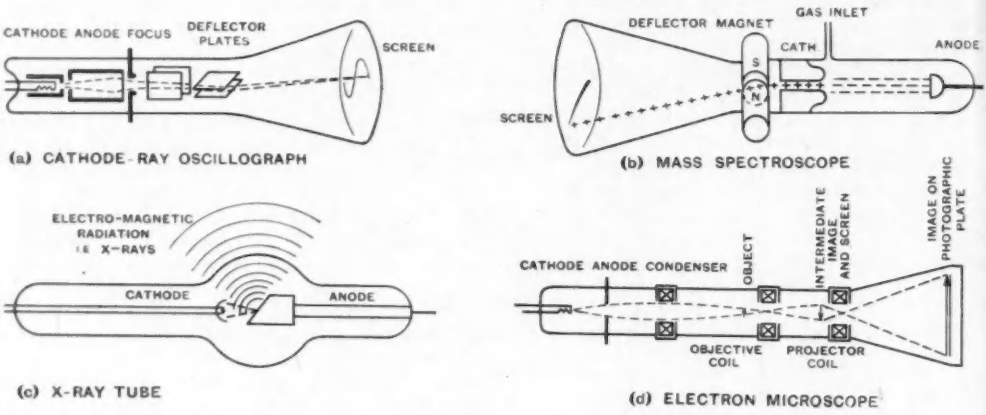


Fig. 5.—Diagrammatic views of electronic "target" devices : (*a*) **Cathode ray oscillograph** (*b*) **Mass spectroscope** (*c*) **X-ray tube** (*d*) **Electron microscope.**

(*a*) *Power supplies.*

The power supply is usually available at one or other of the standard high-tension or low-tension polyphase A.C. distribution voltages. The circuit voltage, however, is dictated by the output voltage or by the voltage required to give the maximum power output from the electronic devices, or the maximum sensitivity of the circuit. It is usually necessary to transform the supply voltage to a voltage suitable for the circuit requirements including rectification to D.C. if necessary. The introduction of a transformer at the input stage provides a convenient opportunity of obtaining heater and auxiliary supplies from subsidiary windings.

(*b*) *Control signals.*

Control signals are of two kinds, primary signals initiating or automatically determining the operation of the electronic circuit and secondary signals derived from the circuit itself for the purposes of safety and stability. As electronic devices are mostly voltage controlled the aim is to obtain the control signal in terms of a voltage and Table 5 indicates some of the methods by which this can be achieved. The signals can be continuous, pulsating, alternating, or intermittent and they can be applied to a control unit in direct differentiated, integrated or time delayed form according to the response required.

5. FUNCTIONS OF ELECTRONIC EQUIPMENT.

The functions of the valve devices can be divided into five main groups as follows :—

Current conversion,
Amplification,
Production of oscillations,
Circuit modification,
Control.

(*a*) *Current conversion.*

The transmission and distribution of electrical energy is most conveniently carried out by means of A.C., but there are many examples where D.C. is desirable for driving variable speed machines or supplying oscillators, or electrolytic loads. In all these applications valve devices function as synchronous switches, multi-anode mercury arc rectifiers acting as electronic commutators to their polyphase transformers. Grid control can be used for voltage control as shown in fig. 6, the relation between the D.C. output and the A.C. power being given by the equation

$$E.I. = k.\eta.e.i. \cos \phi,$$

the interesting point being the variation of the power factor cos ϕ with the D.C. voltage E, the other quantities including the efficiency η being approximately constant and the currents I and i cancelling out.

this means that the inverter can only supply current to a leading power-factor load and generally power-factor correction current has to be supplied to enable the inverter to function This is shown in figs. 7*c* and 7*d*.

TABLE 4.

Device	Operation	Application
Cathode-ray Oscillograph	Electrostatic or magnetic deflection of electron beam focused on fluorescent screen or photographic plate.	High-speed recording recurrent and transient phenomena; measurement of small time intervals.
Mass spectroscope	Electromagnetic deflection of positive ion beam focused on fluorescent screen or on target slot.	Analysis of gas mixtures in petrol, oil, synthetic rubber and explosives manufacture. Separation of isotopes.
X-ray tube	High velocity electrons focused on to target anode producing intense electro-magnetic radiation.	Metallurgy, examination of forgings, castings, welds, complicated internal assemblies.
Electron-microscope	Image of object "illuminated" by electron beam focused on photographic plate by magnetic coil "lenses."	Metallurgy, ultimate structure of materials. Magnification 50,000.

The inverse process of conversion to A.C. from D.C. is illustrated in fig. 7. The latched valve effect (see fig. 7*a*) requires that the incoming valve is opened before the pressures on the alternating side equalize. Electrically

(*b*) *Amplification.*

Amplification follows standard radio practice for low frequency A.C. circuits, but more common is the D.C. amplifier with resistance-coupled stages, with means for limiting dis-

TABLE 5.

Quantity	Derivation of Signal Voltage s and Type of Detector
Voltage V	$s = V$ direct measurement, $V.R_1/R_2 + R_2$ potentiometer, $V.T_2/T_1$ potential transformer, $V.C_2/C_1 + C_2$ capacity divider.
Current I	$I.R.$ shunt, $I.Z$ impedance, $L\,dI/dt$ inductance, $1/C.\int I dt$ capacitance, $R.I.T_1/T_2$ loaded current transformer.
Flux N	dN/dt T search coil.
Speed n	$n.N.c/10^8$ tacho-generator.
Torque Q	$N.I.$ direct measurement on electrical machine, $R.I.$, R function of Q strain gauge, $R.I$, I function of Q in electro-magnetic torsionmeter.
Power W	$E.I.$ watt-meter (valve or electro-dynamic).
Acceleration dn/dt	$d(k.V)/dt$ V function of n, tacho-generator;
Pressure P	s function P piezo-crystal, $R.I.$ I function of deflection in condenser or other type of microphone.
Temperature θ	$I.R.(1-k.\theta)$ resistance thermometer, $k_1\theta - k_2\theta^2$ thermo-couple.
Illumination l	$R.I.$, I function light/unit area photo-cell.
Sound S	function R, L, or C in carbon, inductive or condenser microphones.
Mechanical movement x	Change of R, L or C, carbon pile resistance, slider resistance, variable choke or condenser.
Frequency f	$2\pi fLI$ inductance, $I/2\pi fC$ condenser.

tortion and preventing oscillation. Amplifiers bring weak signals to a strength sufficient for measurement or driving control grids in the power stage.

(*c*) *Oscillation.*

Here again radio-transmitter practice is followed, power being fed back to the grid of the valve from the output side (see fig. 2) to neutralize the losses in the system and permit the building up of the oscillations. Relaxation oscillations used generally for timing-circuits are produced by a charge-discharge circuit with resistance and capacity and a valve or neon tube as the "spill-over" element.

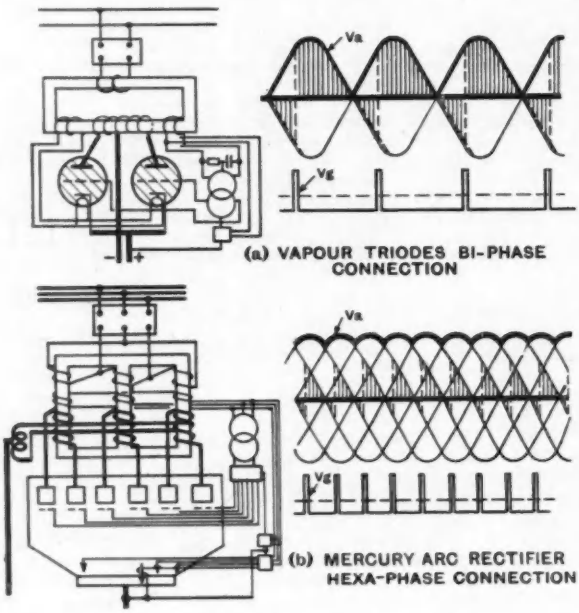


Fig. 6.—Identity of grid control methods for small and large powers.

(*d*) *Circuit modification.*

While all valves limit the operating conditions of their associated circuit, there are several applications of the kind where valves are used to modify the output-wave shapes of a circuit without modifying their characteristics in general, *e.g.*, successive amplification and "chopping" enables a sine wave to be converted to a rectangular wave.

(*e*) *Control.*

Valves are becoming increasingly used in all types of control circuits where precision combined with high speeds of response are required. Both null-methods and compounding are employed; fig. 8 shows an example of the former where the control signal is processed first by voltage amplification and then by phase shifting means to suit the requirements of the vacuum and vapour valves in the amplification and power stages of the circuit.

PART II. THEIR SCOPE IN HEAVY ENGINEERING.

6. THE ENGINEERING VIEWPOINT.

It is proposed to use the term "heavy engineering" in a broad sense for the purposes of this paper to cover both the manufacture and application of engineering equipment, including some of the lighter metals and synthetic materials which are being used on an ever increasing scale in engineering.

The use of any device for engineering purposes implies that it has to fulfil certain standards of reliability and performance; if used as a measuring device it must give consistent readings, its limits of accuracy must be known: if used as part of a manufacturing process it must function reliably to avoid wastage of labour, time or material: if used for operating power-driven machines safety in operation and safety in the event of failure are essential. In addition to all these the project must be justifiable economically, although this is sometimes not easy to assess before installation, particularly when the decision to use the apparatus may have to be made on indeterminate factors such as ease of operation, light load economy, or reduced maintenance.

Fortunately, in the majority of electronic applications the issue is perfectly clear, but there are border-line cases in which the value of the experience gained has led to unexpected new progress and in which the strictly commercial appraisement would not have been the correct long-term policy. On the other hand, some applications do not appear to have been justified on economic grounds and later information has confirmed this opinion.

7. DIRECT APPLICATION OF ELECTRONICS.

The direct use of electronics in engineering can be divided under the following headings:—

Research and testing.

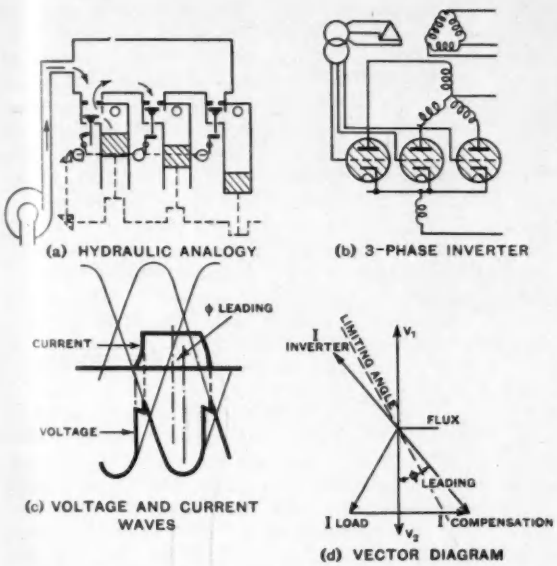


Fig. 7.—Operation of inverter. (*a*) **Hydraulic analogy** (*b*) **3-phase inverter** (*c*) **Voltage and current waves** (*d*) **Vector diagram.**

Manufacture.
Power control.
Safety.

It is proposed to illustrate the theme with a few typical examples from these groups.

Research and testing.

Research to-day can be divided into three main types : fundamental research, applied research and investigation work. In the first of these the interest lies in the ultimate nature of the materials used in engineering and their behaviour under various conditions of loading—mechanical, electrical and magnetic. There are not only metals to be investigated, but also materials such as rubber, porcelain, glass and a host of synthetic compounds produced by the plastics industry. The internal structure of these is revealed by X-ray equipment while thin films can be examined under the electron microscope. The technique of testing material under transient conditions has shown considerable advance with the introduction of electronic methods. The cathode-ray oscillograph enables high-speed records to be taken of the phenomena on an accurate time base, and electronic timing circuits enable the recording gear to be synchronized with the applied stresses. The use of time delay circuits enables test to be applied at a definite interval, only a few microseconds if necessary, after a given phase of the phenomena under investigation has been reached. Examples of this kind are the measurement of the electric strength of gases after the extinction of an arc,

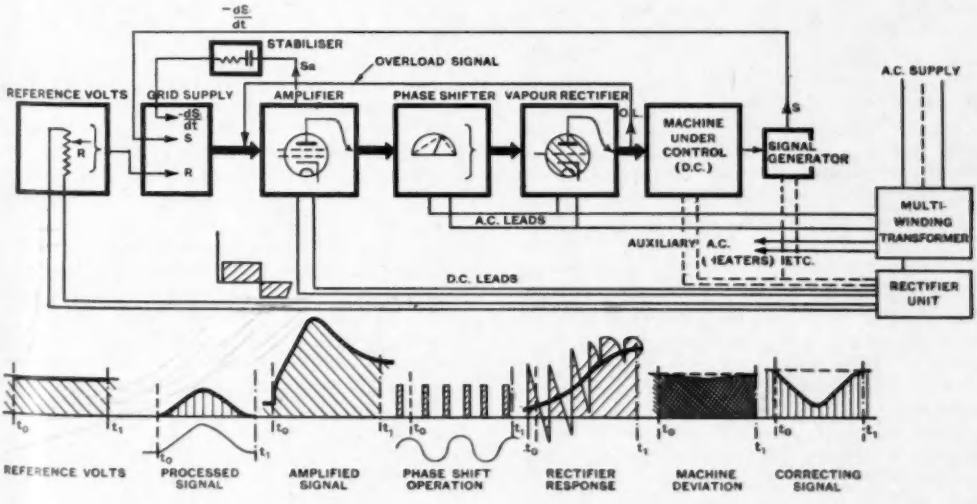


Fig. 8.—Diagram illustrating a method of electronic automatic control.

or the measurement of pressures, temperatures and deflections associated with explosions.

The chief electronic research weapons are the amplifier and the oscillograph, the former designed to bring weak responses to a measurable value; the latter as already indicated, to record high-speed phenomena. The successful application of these depends upon skilled operators being available to set up the equipment, to guard against intruding signals giving spurious results and to interpret correctly the records obtained. Where the operator is familiar with the phenomena under investigation this presents no difficulty, but where new or unknown phenomena are being investigated it behoves the engineer to accept the first results with caution until all the facts have been properly established. These points are mentioned not to discredit the most valuable and important research equipment in general use to-day, but because such checking is so much an instinctive habit of the experienced investigator that it is apt to be overlooked by others not so familiar with the technique. By electronic methods a more exact and detailed knowledge of engineering phenomena is being obtained, and there is, in the author's opinion, scope for improvement in the training of engineers to enable the results of this class of work to be exploited to the best advantage.

In applied research the point of interest is fundamental phenomena exhibited in the working of engineering devices. Again it is in the high-speed processes that electronic methods are particularly useful, especially as much of the machine phenomena is cyclical and can be examined by oscillographic methods. Examples of this are arcing phenomena in arc rectifiers, the operation of filter circuits, studies in electrical and mechanical vibration and the indicating of high-speed engines. Of the non-periodic type the arcing and pressure waves in oil circuit breakers are well known examples. In many instances direct measurements by valve voltmeters is preferable to the oscillograph; in others, the recording of the modulation of an injected high frequency from an oscillator may give the best results. In some cases mechanical phenomena at high speeds can best be studied photographically with a single exposure in darkness, but with high-frequency intermittent illumination to produce successive images on the photographic plate. With an electronic control circuit and a mercury-vapour lamp to produce the illumination the recording can be completely under control in the manner best suited to the investigation.

(*a*) *Testing.*

Testing by electronic methods covers a wide range from the use of special equipment by experts, to the routine checking and gauging by semi-skilled operators. Amongst the spectacular achievements is the development of the technique of the X-ray shadowgrams, which, starting with the checking of the internal alignment of parts, or the continuity of magnetic flux paths using moderate voltage equipment of about 140,000 volts giving results up to 2 in. of shell thickness, has now progressed to 1,000,000 volt equipment for the examination of pressure vessels some 8 in. thick.

A totally different kind of test, designed to detect surface flaws, consists of passing alternating current through a specimen, and as these currents flow near the surface the presence of any flaws increases the length of the current path and the resistance. By comparison with a standard in a bridge circuit with electronic detecting means such as the oscillograph or the "magic eye," faulty specimens can be detected immediately. The possibility of detecting and amplifying small differences has resulted in the automatic gauging of mass-produced components; this, in combination with a warning signal or automatic sorting machine, allows faulty specimens to be rejected. Such methods have been applied to the gauging of piston rings, gear wheels, profiled parts and electrical components. So far as this aspect of electronic application is concerned it is true to say that there is practically no limit to the ingenious circuits that can be devised for widely different gauging and checking purposes.

(*b*) *Manufacture.*

Electronics are playing an increasing part in the manufacture of engineering products particularly where direct use is made of electricity as part of a process. Electricity is used directly in the following processes:—electrolysis, high frequency heating, arc welding, resistance welding, electric furnaces, etc. In each case an essential provision is the precise control of the supply of energy.

Electrolysis forms the basis of production of the raw materials of the light alloys in common use in engineering to-day, and in nearly all modern large plants the conversion from high-tension alternating current to the low-voltage direct current is carried out by means of grid-controlled mercury-arc rectifiers

of the multi-anode or single-anode types. The total installed capacity of this type of plant is of the order of 2,000,000 kilowatts, plant capacities up to 100,000 amperes being built up of units of 5000 amperes, with D.C. voltages up to 800 volts. This represents the static conversion and control of power on the largest scale by electronic means, and with forging, fluxing plated coatings to remove porosity, hardening of gear teeth, sintering of powders, etc.

Eddy-current heating is essentially surface heating, but dielectric heating based upon dielectric hysteresis in an alternating electrostatic field takes place throughout the body of the material. The instantaneous and uniform

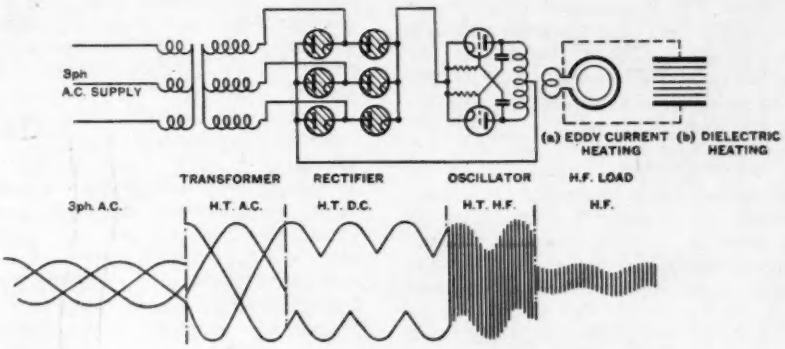


Fig. 9.—Energy conversion sequence in high-frequency electronic heating.

electronic devices running non-stop for periods of several months.

As an example of the application of the oscillator circuit, electronic heating has manifold applications both in the field of eddy-current heating of metals and in dielectric heating of non-conductors. The same type of equipment serves both purposes, consisting generally of a rectifier unit to produce high-tension D.C. at about 10,000 volts to suit the high-vacuum oscillator valves. The high-frequency output from these valves is then transformed to heavy current by step-down coupling coils for the eddy-current heating application or coupled by multi-turn coils to give the high-frequency voltage for the dielectric heating. Fig. 9 indicates the energy conversion process in a unit of this type, using a three-phase full-wave rectifier and a "push-pull" oscillator circuit. Circuits of this type give radio-frequency outputs, units having been built for powers ranging from a few hundred watts to 600 kilowatts. Kilocycle frequencies for induction furnaces of about 300 kW have been obtained directly from mercury-arc rectifiers by arranging oscillatory circuits between the pairs of anodes. The eddy-current heating process is used for such purposes as tempering and tipping tool steels, brazing, heating billets for nature of the dielectric heating is invaluable for treating materials which are normally very poor conductors of heat. The chief application of dielectric heating is the preheating of plastics for moulding purposes and for the manufacture of synthetic resin bonded structures. This has had the result of bringing many materials into the engineering field that were hitherto rejected because of the uncertainty and non-uniformity of their structure when produced by the older methods.

Electronic devices, notably "ignitrons" are used to replace contactors in modern spot-welding equipment particularly the automatic kind. For this purpose two valves are cross-connected in circuit and arranged so that the firing of one valve releases the other. By incorporating additional electronic control means both the number and proportion of each A.C. half cycle used in the operating can be controlled to within close limits.

(*c*) *Power control.*

Power control and in particular the speed control of D.C. motors operated from A.C. supplies offers considerable scope for mercury-vapour devices, from the smallest motors through vapour valves, to the largest through mercury-arc rectifiers. The D.C. voltage may be varied by tap-changing on the rectifier

transformer, by an induction regulator or by grid control of the rectifier, the speed of the motor being given by $n = (V - RI)/N$ and the torque by $Q = N.I.$, where R is the armature resistance, N the flux per pole and I the armature current. The speed of a motor can thus be raised from zero with full torque by raising the armature voltage with full field until the base speed is reached, and thereafter increased with reducing torque by field control. In practice typical ranges are 20/1 below base speed and 4/1 above base speed. Fig. 10 shows the application of electronic control to a small motor, while fig. 11 shows how a group of large motors can be controlled from a single mercury-arc rectifier.

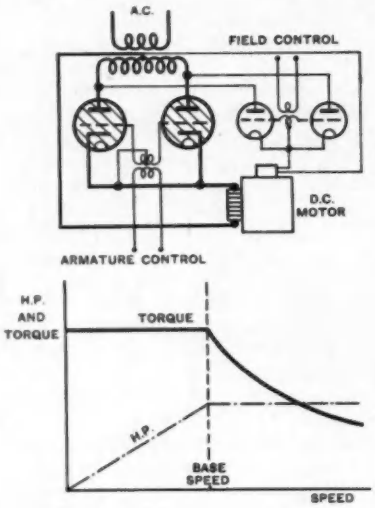


Fig. 10.—D.C. motor electronically operated from A.C. supply.

There are various methods of arranging for reversal of rotation using electronic drives. One is by the use of reversing contactors to reverse the armature connections while the supply is temporarily interrupted by the control grids (see fig. 12*a*); another method is to arrange a second rectifier to stand by reverse connected ready to operate as an inverter to absorb the energy of the motor, thus bringing it to rest under control before running up to speed in the opposite direction (see fig. 12*b*). A third method is known as "plugging" in which small motors are thrown straight over to reverse power so that the motor immediately takes a heavy current under the temporary additive effect of the applied voltage and the back e.m.f. A refinement of this limits the current by an over current device operating on the grid control.

Applications of grid-controlled rectifiers to power control include rectifier-inverter substations for regenerative breaking on railways at 3,000 volts, 1667/1000 kW; rectifier locomotives, one of 2305 h.p. with grid control, another 2/845 h.p. with the rectifier transformer voltage controlled by 28 tap changing steps; 1000 h.p. rectifier-inverter colliery winder, etc.

Uncontrolled rectifiers are, of course, widely used for electric traction supplies of all kinds, including main line and suburban railways, tramways and trolley bus systems, and in which water-cooled, steel tank pumpless and glass bulb types feature. Of special interest are mobile rectifier substations ranging from 100 kW to 1000 kW. These have played an important part during the war by providing emergency supplies, in particular shore to ship supplies to vessels in dock or undergoing repairs.

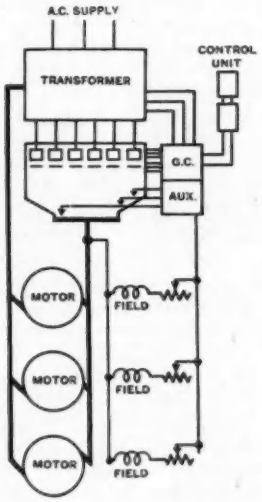
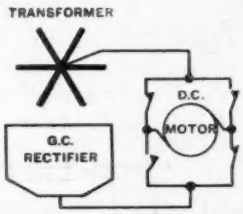


Fig. 11.—Group control of D.C. motors from mercury-arc rectifier.

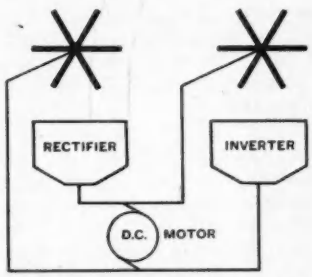
(*d*) *Safety.*

In addition to a wide range of safety applications based upon the interruption of light beams and the operation of photo-electric

cells and amplifier circuits, electronic control offers the opportunity of providing safety in power control circuits. It is possible at practically every stage to introduce over-riding safety signals which guard against mal-operation by the controller, instability, overload,



(a) REVERSING CONTACTOR METHOD



(b) RECTIFIER—INVERTER COMBINATION

Fig. 12.—Alternative methods of motor reversing with electronic drive.
(a) **Reversing contactor method.**
(b) **Rectifier—inverter combination.**

running away, excess temperature, etc. with much less expenditure of energy and greater safety than the equivalent electromechanical system of relays. Also valuable is the smooth and infinitely variable nature of the control.

8. MANUFACTURING PLANT & MACHINE TOOLS.

Valve devices have been applied to a number of different problems in manufacturing plants ranging from smoke control by photo-cells, dust and flue gas precipitation, rolling mill drives in continuous strip mills, edge roll drives in rolling mills, tension control and strip thickness control in rolling mills, reel control in wire drawing and cable making, electric furnace control, conveyor belts in continuous ovens, counting and sorting operations, etc., etc.

A more recent development is the application of electronics to machine tools carrying out functions hitherto performed by mechanical gears and hydraulic control systems. Amongst the various possibilities in this connection are the provision of infinitely and continuously variable speed drives, reversible drives and feed control, the features outlined in the sections on motor speed control and safety being incorporated. Examples of machine tools to which electronic control has been successfully applied include lathes, milling machines, grinders, planers, profiling machines, etc. In these applications the first cost may appear high in comparison with the size of the electric motors, but will be found to compare favourably with alternative methods of control. The main advantages are better finish to the work, particularly with grinding machines because of the close speed control, and considerably reduced operating times where variable diameter or variable depth of cutting is required. Savings in time of 20/1 have been quoted in connection with spar milling.

9. PRESENT EXTENT OF ELECTRONIC APPLICATION.

Up to the present electronics has received considerable support in the technical press, both in this country and in America, and deservedly so as many of its achievements have been of a very high technical order. There is also a general feeling in technical circles that engineering applications will continue and that further developments can be expected. Although statistics are not available for this country, there is evidence that current conversion by mercury-arc rectifiers represent the main application at the present time and there is considerable experience available on electronic welding sets. The other applications, though individually not so numerous, represent in aggregate sufficient experience to encourage the engineer to proceed with the use of electronic methods when the requirements warrant their application.

10. INFLUENCE ON ASSOCIATED PLANT.

Electronic control or operation should not be introduced without careful study of its influence on associated plant and in many instances the best policy is to start afresh rather than adapt existing gear. To quote a few examples, the speed of response can be made almost instantaneous and it is therefore very easy to apply sudden overloads to machines. Some types, such as rolling-mill motors, can withstand such treatment, but most types will require the introduction of a constant-current device to limit the acceler-

ation currents and stresses. Equally significant is the introduction of non-sinusoidal wave forms and saw-toothed D.C. voltages produced by grid control. Contrary to what might have been expected, the commutation of machines under these conditions appears to be generally satisfactory for both large and small machines, due mainly to the smoothing effect of the inductance of the machine itself. Attention must be paid however to increased armature heating with small machines on bi-phase rectifiers and to ventilation requirements when delivering full torque at low speeds. Since rectifiers contain no energy storage means, as for example a flywheel, load fluctuations on very large machines or heavy-current welding sets may be reflected in the A.C. supply system.

Thus, while there may have been some departure from the ideal in the conditions imposed on the associated plant by the introduction of electronic methods, the performance of machines has remained excellent, and this with the immunity of static converting plant to A.C. system disturbances, and their reduced maintenance, has resulted in a better standard of reliability, combined with greater ease and precision of control.

11. ECONOMIC ASPECTS.

The economic aspects of industrial electronics are often involved and the factors to be taken into account are not easily apparent, unless a thorough understanding of the equipment proposed and its application is available. The first cost of control schemes is frequently comparatively high for small powers, as the advantage of the low cost of the valves and other components, which have the benefit of the mass production in the radio industry, is off-set by the polyphase circuits and the manufacture of the special transformers to engineering standards required for industrial purposes.

For large plants where the issue lies between mercury-arc equipment and rotating machinery, the balance is much more favourable, and provided that the voltage is high enough, is frequently decisive in establishing the case for electronic methods. Reverse power or double conversion calls for careful scrutiny because of the duplication of plant involved. Efficiency, power factor and load factor enter into the running costs and in this connection the high light load efficiency of static conversion often shows to considerable advantage.

For manufacturing purposes, other factors, such as convenience in operation, saving of process time or operation time as compared with possible alternative methods, have to be taken into account. The security and precision in handling the controls of an electronically controlled motor, for example, are features which when once experienced, are not easily set aside. Skilled operatives are quick to take advantage of the ease of control by the new method and are often able to increase the output from a machine by an amount greater than anticipated.

To quote another example, the efficiency of a high-frequency oscillator for electronic heating is only of the order of 60 per cent and the power input to the work is even lower; but as the work can be carried out in seconds as compared with minutes or hours by alternative methods the gain is at once apparent. Again, the initial cost may be high, but is soon justified with an adequate load factor.

12. CONCLUSIONS.

Since this paper was begun, there have been startling disclosures about the production of atomic energy in which electronic engines, such as the mass spectroscope have played an important part. Without electronics the war could not have been won, but their peace-time scope lies along the lines indicated in the paper in providing more abundantly man's needs, light, heat, mechanical power, communications and manufactured goods.

High Intensity Mercury Vapour Arc Lamps.

By E. H. NELSON,
G.E.C. Research Laboratories.

1. INTRODUCTION.

THE development of the type of lamp described in this article has been conducted over the past 10 years with the object of producing lamps for use in optical projection apparatus.

The lamp is a development from the high pressure mercury vapour street-lighting lamp introduced in 1933, and its small, nearly spherical, source has led to its being called the "compact source" lamp. In many cases it offers considerable advantages over the carbon arc and tungsten filament projector lamp, because it combines the simplicity and steady burning of the tungsten filament with the high intensity of the carbon arc. In fact, among other valuable properties, it is capable of giving higher source brightnesses than any other known source.

The compact source lamp in 250 watt and 500 watt ratings was commercially available before the outbreak of war. During the war there was a demand for several variants to fulfil special requirements which necessitated the development of new techniques. It is expected that these will be of importance in post war applications.

In this paper the application of the lamp is not considered in detail, the main concern being with the many interesting problems which were solved during its development. The large scale commercial application of these lamps involves many considerations, both economic and technical, and it is hoped to discuss these considerations in detail in a later paper.

2. DEVELOPMENT UP TO 1939.

(a) Lamps.

The chief characteristics of high pressure mercury vapour lamps are well known and have been described in this Journal.[1] The first lamps were intended for street and general service lighting and were designed to have high luminous efficiency.

The essential feature of a lamp for optical projection work is that it should provide a source of high brightness.[2] Brightness is measured in candles per sq. cm. of the radiating surface (or column in the case of a discharge lamp) these units being known as "stilb." The table below gives representative figures for various types of source.

Tungsten filament—Up to 2,000 stilb.
Carbon arc (pure)—10,000—25,000 stilb.
Carbon arc (high intensity)—50,000—100,000 stilb.
Mercury vapour arc—Up to 200,000 stilb.
The sun—180,000 stilb.

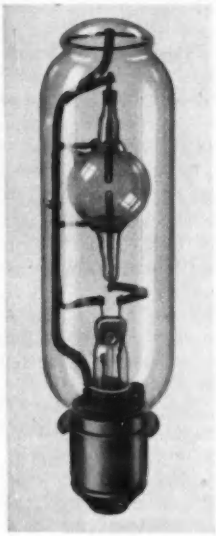
In order to achieve a high brightness with the mercury vapour arc it is necessary to concentrate the source so that large amounts of energy are radiated from a small volume of discharge. Preliminary estimates indicated that, provided the luminous efficiency of the arc remained at not much less than 50 lumens per watt, an arc length giving a rating of about 70 watts per millimetre of discharge would give a brightness of about 20,000 stilb, when operating at a mercury vapour pressure corresponding to a voltage drop of about 20 volts per millimetre.[3, 4, 5, 6]

Fig. 1 shows the 250 watt and 500 watt lamps which were the first embodiment of the high wattage density compact source lamp.

The 500 watt lamp shown in fig. 1(a) is similar in construction to the street-lighting lamp, having an inner bulb, in this case of quartz, not glass, containing two tungsten electrodes. There is the usual electrode activating material and rare gas filling to facilitate starting and the initial stages of operation.[7] When the lamp is in full operation the arc burns between the tips of the tungsten electrodes which are 5·5 mms. apart. The arc is prevented from spreading sideways, and the lamp voltage brought up to a reasonable value, by having sufficient mercury in

the lamp to develop a mercury vapour pressure of about 10 atmospheres.

The effect of this high pressure is to cause the discharge to constrict into a narrow



ig. 1(a).—500 watt type M.E. mercury vapour arc lamp.

column. Fig. 2 shows a typical arc brightness distribution for a lamp of this type, operating at a pressure resulting in a voltage drop of 12 volts per millimetre (approx. 10 atmospheres) and a wattage rating of 90 watts per millimetre of arc.

The 250 watt lamps in fig. 1 (b and c) have an arc length of 3·75 mms. and operate at about 70 watts per millimetre and 18 volts per millimetre of arc and have a peak brightness of about 20,000 stilb. The mercury vapour pressure is made about 20 atmospheres in order to keep the lamp voltage about the same as in the 500 watt lamp. Fig. 1(b) shows a 250 watt lamp mounted in a metal box, and fig. 1(c) shows a more recent version in a glass outer jacket.

The colour rendering properties of these lamps are not very different from those of the well known 400 watt street-lighting lamp, and since the earliest days attempts have been made to improve the spectrum ; notably by the use of additional metallic vapours and the use of very high pressures of mercury.[2] In the case of the relatively low brightness street-lighting lamp a considerable advance was made by the combination of the first of these methods with fluorescent materials but, in general, it is not practicable to use fluorescent light sources in applications where high brightness is necessary. We describe below recent developments which have resulted in high brightness metal vapour arc lamps having greatly improved colour rendering properties.

(b) Circuits.

The circuit conditions required for high intensity mercury vapour arcs are similar to those necessary for the well known mercury vapour street-lighting lamp.

In common with most arcs or discharge devices the mercury vapour discharge has a "negative characteristic" and requires a series impedance to enable it to run stably. For D.C. operation a resistance is used, but for A.C. operation a choke is commonly employed since it is less wasteful of electrical energy. With a choke stabilizer, however, the overall power factor of the circuit will be low unless a suitable correction condenser is shunted across the main supply.

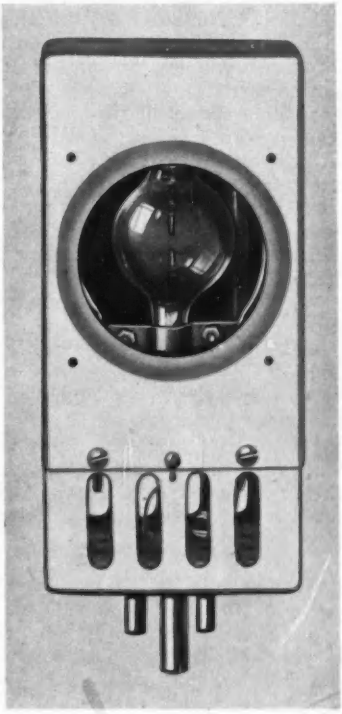


Fig. 1(b).—250 watt type M.E. mercury vapour arc lamp.

The lamps described in this paper will not start reliably on supply voltages of less than about 230 volts D.C. or 180 volts A.C. and for supplies of less than these values a starting device should be used. Some of these devices are discussed later in section 3(g).

Fig. 1(c).—250 watt type M.E. mercury vapour arc lamp.

Conditions for stable operation of a 250 watt high brightness lamp on D.C. are shown schematically in fig. 3.

The circuit is shown at (*a*). Curve A shows the relationship between lamp current and lamp voltage when the lamp is operating at full pressure. The shape of this curve is characteristic of many arc discharges and it will be noticed that, in the region of the working current, the lamp voltage is practically independent of current. This illustrates the fact that these discharges do not obey Ohm's Law and shows the need for a stabilizer to limit the current passed.

A typical stabilisor characteristic is shown at B. Curve C shows the combined lamp and stabilizer characteristic. D shows a typical mains voltage level cutting the characteristic C at E and F. With the values used here the circuit will operate stably at F but not at E because the overall circuit characteristic is negative in slope at E and consequently unstable.

It will also be evident that the lamp will not operate on a supply voltage lower than 90 volts since no point on the circuit characteristic lies below this value.

3. WAR-TIME DEVELOPMENT.

Development during the war years followed two main lines. One was the extension of the wattage dissipation and arc brightness by a factor many times that of the 500 watt and 250 watt lamps. The other was the development of methods of avoiding some of the difficulties arising from the characteristics of the mercury arc when employed in specialised apparatus. For most war-time applications the colour of the source was not of great importance, but the techniques developed for other purposes made advances in the direction of improved colour rendering properties much simpler than they would otherwise have been; and due advantage has been taken of this fact.

These lines of development are considered in detail under the following headings :—

(*a*) Wattage and brightness range.
(*b*) Colour.
(*c*) Flashing.
(*d*) Seals.
(*e*) Electrodes.
(*f*) Bulbs.
(*g*) Run-up time and re-starting.
(*h*) Burning position.

(a) Wattage range.

Since the inception of the 500 watt compact source lamp there has been a constant effort to extend the rating of mercury lamps into higher wattages. This effort has been prompted by the demand for very powerful light sources, simpler and cleaner in operation than the high-current-density carbon arc.

In the early days of the war there was a request for a lamp of 10—50 kW rating having the highest possible brightness. This was far in excess of anything that had then been contemplated but it was developed through a steady progression of lamps from 5 kW, 10 kW, 15 kW, 25 kW, to an experimental 50 kW lamp which was burnt in 1941.

This lamp was never put into operation because it was not then possible to achieve the small source necessary to obtain the required arc brightness, but a great deal of valuable knowledge was gained in the construction and behaviour of powerful mercury vapour arcs.

The 25 kW lamp shown in fig. 4 was brought

to an advanced stage of development during this period. The lamp shown operates on D.C. in a vertical position, without an outer jacket. It has a quartz bulb 150 mms. in diameter and operates at a pressure of about 5 atmospheres of mercury vapour which gives an arc voltage of some 6 volts per millimetre of arc. At 25 kW the arc rating is 1250 watts per millimetre and the peak brightness is about 100,000 stilb.

Many experimental 5 and 10 kW lamps have been made to a similar design, and operated for periods up to 100 hours. At the moment it is too early to say what applications these very powerful lamps will have in the future.

Fig. 5 shows the relationship between arc brightness and lamp current for various voltage gradients along the arc in mercury vapour lamps of the type described in this paper. The broken lines connect points of constant watts per centimetre of the arc. The importance of the wattage loading of the arc in relation to electrode heating and lamp life is discussed in section 3(*e*).[5]

(b) Colour.

The colour rendering properties of the mercury vapour arc, whilst good enough for many purposes, are not satisfactory for all applications. For example, when colour discrimination is important, the lack of red and blue in the spectrum is a serious disadvantage. For this reason the ordinary mercury vapour arc lamp is not suitable for colour photography or for the projection of colour films.

Fig. 6(*a*) shows diagrammatically the spectral distribution of the light from a mercury vapour arc operating at a pressure of a few atmospheres. The most prominent visible spectral lines are shown in heavy type and it will be seen that these consist of two lines giving yellow light and one line giving green

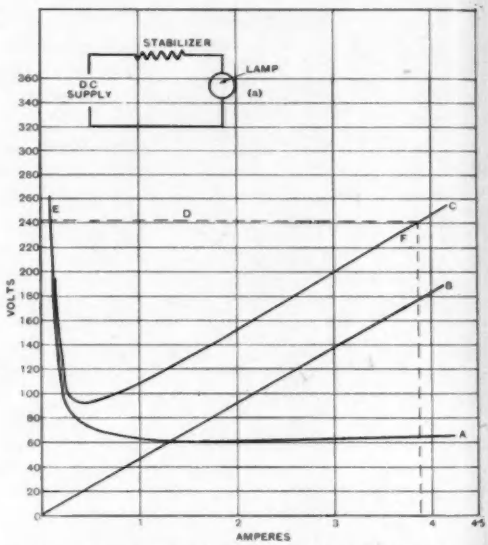


Fig. 3.—Lamp and circuit characteristics for 250 watt lamp operating on D.C.

light. The fact that these three lines fall near to the peak of the average visibility curve (fig. 6(*d*)) accounts in some measure for the high efficiency of mercury vapour light, because a large proportion of the radiated energy is emitted at wavelengths where it is physiologically most effective.

The relatively small amount of radiation in the red and blue ends of the spectrum accounts for the poor colour rendering of mercury vapour light where these colours are concerned, although, due to a few weak lines and the presence of a faint background of continuous radiation, the light is not entirely lacking in colour discrimination in these regions of the spectrum.

It has long been known[2] that this disadvantage may be partially overcome by a number of methods used separately

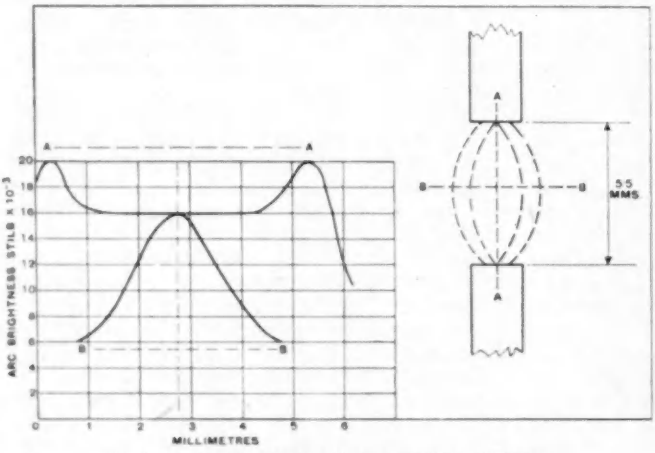


Fig. 2.—Arc brightness distribution for 500 watt lamp.

or in combination :—

(1) Hot bodies in the discharge : These enhance the background of continuous radiation and are particularly effective in contributing red light.[9]

(2) Very high vapour pressures : At vapour pressures of some 60 atmospheres and above the continuous background radiation becomes much enhanced. The improved colour of the high intensity water cooled lamp is largely due to this effect.[10]

(3) Addition of other metallic vapours : Lithium, zinc and cadmium vapours have all been used in conjunction with mercury vapour in order to introduce the additional spectral lines of these elements.

In the employment of additive metallic vapours with mercury vapour, the main consideration is that the additives should contribute light in the red and blue ends of the spectrum ; but many other properties have also to be taken into account. The use of cadmium and zinc vapour in combination with mercury vapour has shown that a considerable improvement in colour rendering properties, compared with mercury vapour alone, may be achieved. Lamps employing mixed mercury-zinc-cadmium vapours have reached an advanced stage of development with the result that metal vapour arc lamps have been made experimentally whose colour rendering properties may make them, in some fields, a competitor of the H.C.D. carbon arc even where colour is important.

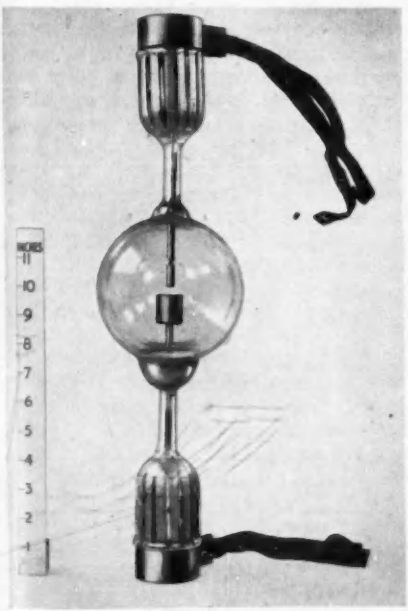


Fig. 4.—25 kW mercury vapour arc lamp.

Fig. 6 (*b* and *c*) shows the prominent visible spectral lines of zinc and cadmium vapours respectively when operating under discharge lamp conditions. Both vapours show strong lines in the red and blue regions. Cadmium shows an additional green line. It will be clear that, by arranging the proportions of mercury vapour to the vapours of either or both of these metals so that the visible radiated energy is shared roughly equally between them, a considerable improvement in colour rendering is to be expected. Much of the development work of the past year or so has gone into solving the problem of obtaining the best values for the vapour pressures of the mercury and its additives. On these values depends the colour rendering properties and the efficiency of the finished lamp and, as a result of recent work, we are now able to produce lamps experimentally which are better, both in colour and efficiency, than anything that was considered possible a few years ago. In fact, purely from the point of view of adding red and blue, it is now possible to over-correct the spectrum.

When it is remembered that in improving the colour of mercury vapour lamps one must add energy in a part of the spectrum where it is necessarily inefficiently employed, it will be understood that, in general terms, colour correction will always involve some sacrifice of efficiency. Although, therefore, it is to be expected that, compared with the ordinary mercury vapour arc, there will be a worse performance with the improved colour lamp, this poorer performance is not necessarily of great importance. Rather, it is necessary to compare the metal vapour colour corrected arc lamp with existing light sources, *i.e.*, the carbon arc and tungsten filament lamp.

The tungsten filament lamp, in addition to the disadvantages pointed out earlier, is not altogether satisfactory in its colour rendering properties. The excess of red light and lack of blue light can be corrected quite fully by the use of suitable filters, but the resulting low efficiency is a serious drawback.

Whether the compact source lamp will rival the H.C.D. carbon arc will depend largely upon the type of optical system in which the lamp or arc is to be used. It appears that, in some applications, one may expect at least comparable overall efficiencies. The position

is less favourable to the metal vapour lamp where a very small source is called for, since the combination of very high brightness and good colour rendering presents a problem in addition to those of obtaining each separately.

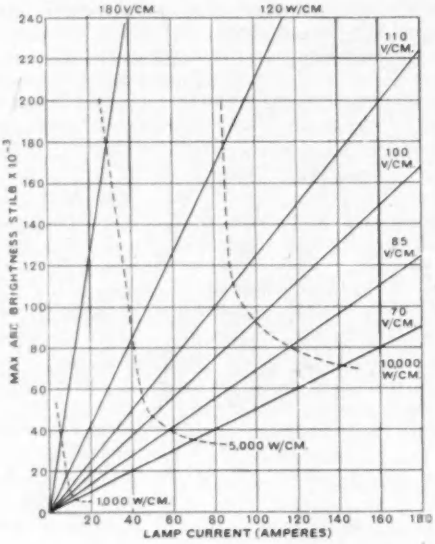


Fig. 5.—Brightness of mercury vapour arc lamps.

On the other hand there is no additional difficulty in making the very high wattage lamps described in this paper, and lamps of 25 kW rating have already been made in the form of the lamp shown in fig. 4.

(c) Flashing.

For certain applications where a powerful source of light is required, the light is needed for very short periods only. Typical instances are signalling lamps and lamps for photography. In these cases the well known technique of flashing may be used to extend the wattage range momentarily far beyond the normal rated wattage of the lamp.

The light output from the mercury arc follows the lamp current practically instantaneously, whereas both the carbon arc and tungsten filament take an appreciable time to adjust themselves to new current conditions. Moreover, the tungsten filament lamp cannot be heavily overloaded for any appreciable length of time before the filament melts.

In this connection it is interesting to note that the life of the mercury vapour arc is not much affected by variations in mains voltage which would give rise to serious trouble in tungsten filament lamps. The full possibilities of flashing techniques applied to mercury vapour arcs have not yet been worked out. It seems likely that the method will have important applications in certain fields.

(d) Seals.

One of the most interesting problems to be solved in the development of very high wattage lamps was the design of a quartz-metal seal capable of carrying currents up to 300 amperes at temperatures up to 1000 degs. C. and pressures up to 10 atmospheres.

When it is desired to seal an electrical conductor through glass it is usual to select a material for the lead which has a thermal expansion about the same as that of the glass to be used. For this reason low expansion glasses usually employ tungsten or molybdenum wire leads; these two metals being refractory enough to withstand the high temperatures of seal making and having relatively low coefficients of expansion.

Low expansion glasses often have expansion coefficients of $3\text{–}6 \times 10^{-6}$, but quartz has a value of $0{\cdot}5 \times 10^{-6}$, *i.e.*, very much lower than any known metal or alloy which is suitable in other respects to form a seal wire. Of course graded seals may be used with quartz, and a series of glasses of gradually increasing expansion coefficients sealed between the quartz and the lead wire. This method, however, is not generally acceptable for high brightness mercury arcs because

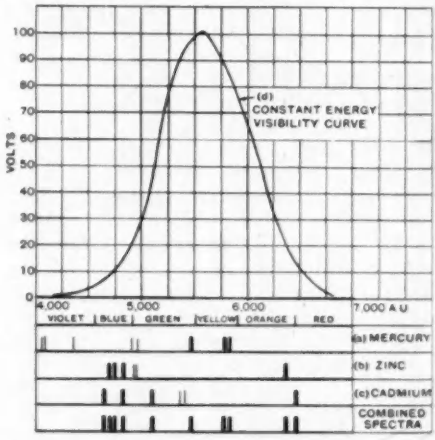


Fig. 6.—Spectral distribution of light from mercury vapour arc with additive metallic vapours.

graded seals are difficult to make for operation at the high temperatures necessary for the burning of mercury vapour arcs. In fact, minimum wall temperatures required to maintain the mercury vapour pressure are so high that it would be difficult to avoid softening of the grading glasses.

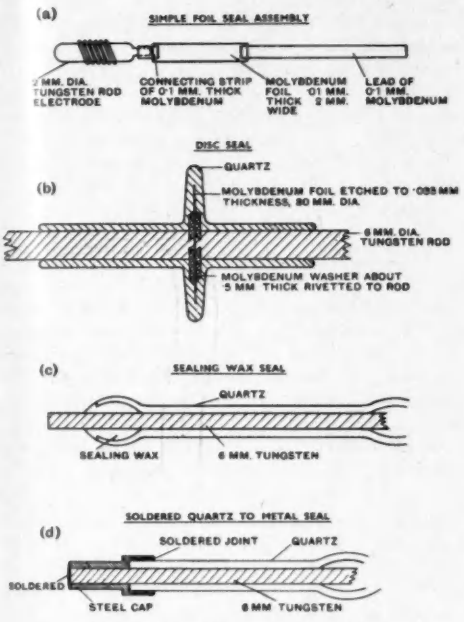


Fig. 7.—Types of quartz-metal seals.

However, all these difficulties may be avoided by the use of the so called "Foil Seal." These seals employ the same principle as the metal-glass seal in which glass is attached to a metal piece which may have quite a different coefficient of expansion from that of the glass, but is of such thin section that it cannot exert sufficient stress on the glass to fracture it.

A simple form of the foil seal is shown in fig. 7(*a*) in which a short length of 0·01 mm. thick molybdenum foil 2 mms. wide has an electrode attached to one end and a lead to the other end. This assembly is enclosed in a tightly fitting evacuated quartz tube and the quartz then strongly heated around the foil with an oxy-coal gas blowpipe. This results in the softened quartz collapsing onto the foil, and it is found that the contact between quartz and foil is so intimate that gas will not leak along the interfaces. The unwanted end pieces of quartz tube are cut away and the assembly may then be fused into the lamp bulb. Since the seal employs only quartz and molybdenum it is capable of withstanding very high temperatures—up to 1400 degs. C. in an inert atmosphere, or about 500 degs. C. in air. This property combined with its small size and mechanical robustness makes it eminently suitable for use in mercury vapour lamps with quartz envelopes.

The seal shown schematically in fig. 7(*a*) will carry a current of about 3 amperes continuously, and it is clear that the capacity may be increased by arranging several foils in parallel.

When it became necessary to make seals capable of carrying currents up to 300 amperes a new approach to the problem was needed because a single seal containing 100 small foils in parallel would have been tedious and difficult to make. After considerable research it was found possible to seal quite heavy strips of molybdenum sheet through quartz; the essential factors being that the edges of the strips should be very thin and the surface of the metal very clean and slightly roughened.

Both these conditions were achieved by cutting a strip of 0·1 mm. molybdenum sheet 10 mms. wide and etching it electrolytically. It was found that preferential etching takes place along the edges of the strip resulting, at the end of the process, in a strip about 8 mms. wide and 0·05 mm. thick in the centre tapering down to about 0·01 mm. thick at the edges.

A single strip of this size when sealed into quartz by the method described above was found to be capable of carrying a current of about 20 amperes continuously. Seals containing several of these strips in parallel were made, and the 25 kW lamp shown in fig. 4 has seals each containing 16 strips, giving a seal capable of carrying over 300 amperes continuously.

When it is remembered that a few years ago it was considered difficult to make a seal to carry 1 ampere through quartz, it will be appreciated that the development outlined above indicates a surprisingly rapid and successful advance.

Various modifications of the foil seal have been proposed. Among the most interesting is that shown in fig. 7(*b*) in which the current is carried by heavy metal rods while gas is unable to pass round the edge of the molybdenum foil diaphragm.[11] This method avoids the difficulty of passing heavy currents along thin foil.

Alternative and quite different methods of making sealed joints between quartz and

metal are shown in fig. 7 (*c* and *d*) where (*c*) shows a simple waxed joint and (*d*) shows a joint made by soldering metal to quartz after metallizing the quartz with silver.

These alternative methods offer, in principle, a superior form of seal because the current carrying member may be made of very substantial cross-section. In practice, however, several technical disadvantages are encountered and at present the foil seal offers the most satisfactory method of making even the highest current seals.

(e) Electrodes.

Tungsten is the material used for both anode and cathode electrodes in the mercury vapour arc since it is the most refractory metal and will withstand the intense heat of the discharge where it terminates on the electrode tips.

The 25 kW lamp shown in fig. 4 is intended for D.C. operation. The lower electrode is the anode consisting of a cylindrical block of tungsten 18 mms. diameter and 20 mms. long. The cathode is a rod of tungsten 6 mms. diameter.

It has been stated above that this lamp has a peak brightness of about 100,000 stilb. and a wattage rating of 1250 watts per millimetre at 6 volts per millimetre. For a lamp of this design, these figures probably represent a maximum if a reasonable life is to be achieved. It is easily possible (*e.g.*, by shortening the arc length) to increase the arc wattage loading and so increase the brightness of the arc, but it is found that the tungsten anode is then heated so intensely that it melts locally and evaporates rapidly. The bulb may then become seriously blackened in a few minutes.

To minimise this effect the anode is made very large, but it is not easily possible to obtain high density blocks of tungsten larger than the size mentioned. Moreover, due to the increased length of heat conducting path to the surface of a larger anode, the advantage of the increased radiating surface is not fully realised.

These considerations appear at the moment to impose a limit on the brightness obtainable in high wattage lamps of this design. There are, however, methods of avoiding the difficulty, among which may be mentioned force cooling the anode by water or the like, increasing the emissivity of the tungsten by special coatings and the use of multiple anodes bunched into a number of terminations.[12]

This brightness limitation does not appear to be so severe in low wattage lamps where the dimensions of the arc may conveniently be small compared with the anode dimensions. Experimentally, brightnesses as high as 200,000 stilb have been obtained in lamps of 1 kW rating.

Since the cathode is not subject to such severe heating as the anode and is, in fact, in some measure cooled by the extraction of electrons from it, a much smaller electrode may be used. The idea immediately suggests itself that, if a lamp were operated on A.C., the two electrodes could be made identical and intermediate in size between the anode and cathode of a lamp operating on D.C. at the same arc loading.

This is, in fact, the case, but a new difficulty arises with A.C. operation at very high loadings. The problem is not fully understood but it appears that the rapid heating and cooling cycle through which the electrodes must pass on A.C. causes pitting of the electrode surfaces which leads to evaporation of tungsten and bulb blackening.

A considerable amount of work has been done on this problem and many interesting features disclosed. At present it may be said that for high wattage lamps of the simple type discussed here, the maximum arc loading for a satisfactory life is roughly the same for both A.C. and D.C. operation.

This loading gives a peak arc brightness of about 100,000 stilb which is about the best obtainable with 150 ampere H.C.D. carbon arcs.

(f) Bulbs.

Fused silica was the material used for the envelopes of the first compact source lamps; and no more satisfactory material has been found since.

The essential properties of a lamp bulb for high brightness mercury vapour arcs are that it should be :—

(1) Capable of withstanding temperatures up to 1200 degs. C.
(2) Transparent.
(3) Of high mechanical strength.
(4) Chemically and physically stable even at the highest temperature.
(5) Capable of being formed to shape, and of being machined or worked to take seals and pumping stems.

Transparent fused silica fulfils most of these conditions fairly well but there is no doubt that it would be possible to improve lamp performance very materially if a stronger, more refractory substance were available. With such a new material it would be possible

to operate lamps at higher pressures and consequently higher brightnesses at least in those wattages where the electrodes do not impose a limitation.

For lamps burning in free air of the type shown in fig. 4, it may be said that the maximum permissible bulb loading is about 35 watts per sq. cm. This will result in a maximum inner wall temperature of about 1100 degs. C. Above this temperature fused silica will deteriorate rapidly due to re-crystallization. That is, it will lose its transparency and fall greatly in mechanical strength.

A great deal of work has been done in order to increase the permissible quartz loading, either with a view to decreasing the lamp size for a given wattage or in order to increase the lamp wattage in a given size of bulb. It must be remembered that the internal pressure that a spherical bulb will withstand is dependent on its diameter, and consequently it is often very advantageous to reduce the bulb size of a lamp of given wattage and so enable higher working pressures of mercury vapour to be used.

Forced cooling of the bulb has been used experimentally to good effect, and both air and water have been employed as cooling media. It is easily possible to double the maximum permissible quartz loading using forced air cooling and, by using water cooling, the quartz loading may be increased many times.

It may be found possible in the future to increase wattage loadings much beyond what is possible to-day. With the removal of this present limitation even more compact and brilliant sources will become available.

(g) Time of run-up and re-starting.

One of the disadvantages of mercury vapour arcs is the delay experienced in achieving full brightness on starting the lamp, due to the time taken to heat up the bulb and to evaporate the mercury. A further delay occurs when a lamp is switched off and on again, since it is necessary to wait several minutes while the mercury vapour cools and its pressure drops to a value at which the lamp will start on the usual supply voltages.

For certain war-time applications it was essential that a high brightness source should be instantly available. This requirement was met by burning the lamp continuously at about 50 per cent nominal watts in order to keep it warm and maintain the mercury vapour pressure near to its full value.

It is found that when a lamp is burnt under these conditions (known as "simmering"), the life is almost indefinitely long. Owing to the peculiar characteristics of the mercury arc it is not usually satisfactory to reduce the lamp watts by additional series impedance, but the circuit modifications required are quite simple and by the operation of a switch the lamp may be switched up to full watts and the full light made instantly available.

The other important problem was how to restart a lamp quickly. It is well known that the starting voltage of an arc discharge depends, among other things, on the pressure of the surrounding gas. When a high pressure mercury vapour lamp is switched off after operating at full watts it contains mercury vapour at several atmospheres pressure and the voltage necessary to initiate a discharge between the relatively cold electrodes is several thousand volts. In the course of a few minutes the lamp cools and the mercury vapour pressure drops. The necessary starting voltage also drops until the lamp is quite cool and will start on ordinary mains voltage supplies.

The problem, therefore, is to start a lamp when it is hot and containing mercury vapour at high pressure. There have been developed several methods by which this may be done, and, by a slight complication of the lamp or circuit, the difficulty may be considered to be eliminated as a serious disadvantage. The complexity of the modifications depends on the speed at which it is desired to restart the lamps. If a delay of 30 seconds is of no consequence the re-starting unit may be made very light and simple.

Of course, when a lamp is re-started in this way it is already in a relatively high pressure state and assumes its fully operational condition almost immediately.

By these means, delay in utilising the light from mercury vapour arcs may be largely eliminated and the light made as quickly available as that from a tungsten filament lamp.

(h) Burning position.

A feature of the 500 watt and 250 watt mercury vapour lamps was the necessity for burning them in one position only. In this they were similar to most tungsten filament projector lamps and to many carbon arcs. In many applications of these lamps, however, it is desirable to operate the lamp in other positions than with the arc vertical, as, for instance, when a condensing optical system has to be tilted and turned to throw a beam of light in any direction.

Furthermore, it is often possible to avoid

obscuration of condensing mirrors or lenses by the massive electrodes of the larger wattage lamps, if the lamp is tilted with respect to the optical axis of the system.

In general it is necessary in designing a lamp to ensure fairly even temperature distribution over the bulb wall. To this end, lamps designed for vertical burning are often made with the arc below the mid-point of the bulb in order to avoid overheating of the upper parts of the bulb by convection streams in the mercury vapour. Consequently it is often necessary to prescribe quite rigidly the burning position of a lamp.

If a lamp such as the 500 watt lamp shown in fig. 1(*a*), which is intended for vertical burning cap down, were burnt in a horizontal position, the stream of hot vapour rising from the arc would strike the wall of the bulb above the arc and overheat it. Furthermore, the lower part of the bulb would be likely to be so cool that mercury might condense there and the mercury vapour pressure never rise to the correct value.

It has been found that this difficulty may be overcome quite simply by the use of a magnetic field. The hot "flare" rising from the arc is found to behave in the same manner as a flexible electrical conductor carrying current in the same sense as the arc. Consequently the "flare" may be deflected by a magnetic field. It is found that quite a weak magnetic field arranged so that it passes horizontally through the arc and at right angles to the current in the arc will deflect the "flare" downwards when the direction of the field and current are in the correct relationship.

This is, in outline, a common method of operating lamps horizontally. It will be clear that the method is quite flexible; indeed, it is often possible to arrange to direct the arc "flare" wherever it is needed.

4. APPLICATION.

The 250 watt and 500 watt lamps first mentioned in this paper were already finding commercial application before the outbreak of war. The war interrupted the normal market development of the lamps, but large numbers of them were instead supplied for war purposes. In addition, several specialized types have been supplied for experimental and secret processes connected with the war effort.

The rapidity with which these lamps will come into general use and the extent to which they may be expected to replace the tungsten filament projector lamp and the carbon arc is not easily estimated. They are at present used, among other things, for profile projection, black and white film projection, certain forms of floodlighting and photomicrography. The combination of high brightness, high efficiency and simplicity makes them very desirable for many applications. Most of their inherent disadvantages have been already overcome, and there seems no doubt that there should soon be a commercial demand for them.

It is hoped to consider these matters in a future paper, which will deal in detail with the whole field of applications. In the meantime, the brief sketch of the new techniques which have been studied in this field of discharge lamp development may serve to indicate some of the interesting possibilities which further research may unearth.

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Low-Oil-Content Outdoor Circuit Breakers.

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Witton Engineering Works.

INTRODUCTION.

RECENT developments in the design of heavy duty metalclad switchgear have already formed the subject of an article in this Journal.* The switchgear then described incorporated a new range of low-oil-content circuit breakers of an extremely simple and compact design. They are of the double-break type with robust, earthed steel-plate tanks, and are distinguished by their reduced dimensions and low oil content, which compare very favourably with that of many so-called "live tank" circuit-breakers. It was an obvious development to adapt this line of circuit breakers for use both in cubicles and also out of doors. The object of the present article is to describe the outdoor breakers which during the last few years have been developed from the original metalclad breakers.

Since supply systems very frequently comprise both indoor and outdoor substations, the advantages of employing the same fundamental design of breaker alike for metalclad, cubicle and outdoor installations are obvious from the points of view both of the user and manufacturer. The main and arcing contacts, the arc control pots, the main insulation and many parts of the circuit breaker mechanism are identical in the three cases, and the same types of operating mechanism may be used for all three types of breaker.

It may be remembered that the metalclad switchgear mentioned above is available for voltages from 6·6 kV to 33 kV. The outdoor circuit breakers are available for the same voltages and, in addition, 66 kV breakers of similar design have been developed for outdoor installation. The range of breakers available is shown in Table I. It will be seen that in some cases two variations of the fundamental design can be supplied. The single-tank type of construction is in general to be preferred for the lower voltages and breaking capacity ratings, or where it may be convenient to be able easily to transport the breakers. For the higher voltages it is in general better to use the type in which each phase is in a separate tank. The centres of the phases can then be made equal to the conductor centres in the remainder of the installation, so that an extremely neat layout of the substation becomes possible. All the circuit breakers have been fully short-circuit tested in the High Power Testing Laboratory at Witton, and comply with the relevant British Standards.

TABLE I.
Standard Low-Oil-Content Outdoor Circuit Breakers.

System Voltage	Breaking Capacity MVA	
	Single Tank Breaker	Three Tank Breaker
kV		
6·6	150 250 350	
11	150 250 350	
22	350 500	
33	500 750	500 750 1000 1500
66		500 750 1000 1500

SINGLE-TANK CIRCUIT BREAKERS.

The 33 kV breakers in this range were originally developed for use in the pool of emergency spare switchgear which was prepared just before the outbreak of war. Fig. 1 shows one of these breakers, which were rated at 33 kV, 500 MVA, 600 amperes. The breaker, complete with its operating mechan-

* *G.E.C. Journal*, Vol. XII, No. 3, February, 1943.

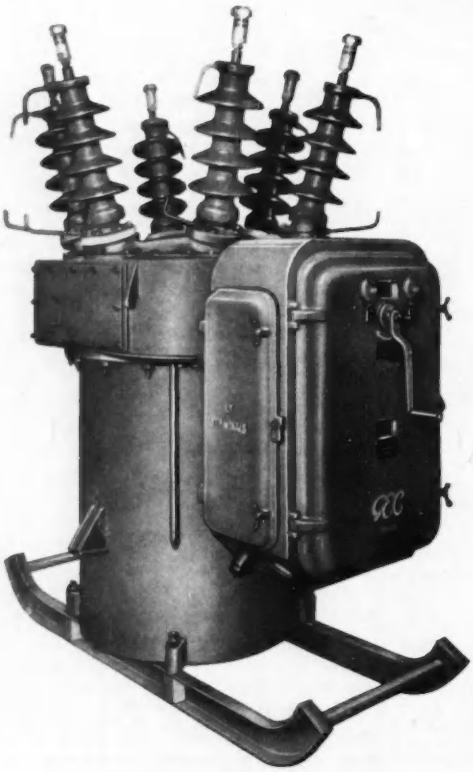


Fig. 1.—33 kV 500 MVA floor mounted single tank circuit breaker, with hand-wound spring operating gear. Many of these breakers were supplied to the C.E.B. for use as emergency spares during the war.

ism, was mounted on skids in order that it could be easily manœuvred into position. In fig. 2 is shown a 33 kV 750 MVA single-tank breaker, mounted in a frame, together with its solenoid operating mechanism.

The top plate of the breaker consists of a strongly ribbed welded steel box which supports the bushings and acts as an expansion chamber for the gas generated in the circuit breaker during operation. It provides accommodation for the actuating levers of the moving contacts and supports the moving contact guide and dashpot. Suitable sub-divisions inside the box serve as housings for the current transformer cores and secondaries, which surround the bushings. Covers are provided by which the transformer cores, secondaries and connections may be easily examined. A transformer may be removed by merely removing the bushing; this operation may be carried out without disturbing the setting of the contact. The bushings themselves are provided with flanges which are bolted to wedge shaped blocks which in turn are bolted to the upper surface of the top plate. The lower ends of the bushings are steadied by being gripped by packing gland supports bolted to the underside of the top plate. The tank is of circular form and is bolted to the top plate by a number of short studs and nuts; the flanges are of the metal to metal type. The tank is provided with a lining of insulating material.

Fig. 3 shows the moving contacts which are carried by synthetic varnish impregnated paper insulators suspended from a common cross-bar which in turn is attached to a cylindrical member sliding in an outer cylindrical guide. The inner member carries a piston which, in conjunction with the outer member, forms

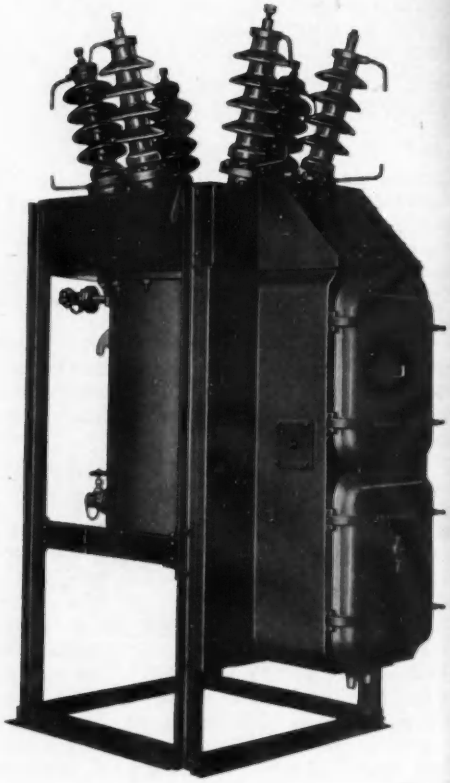


Fig. 2.—33 kV 750 MVA frame-mounted single tank circuit breaker with solenoid operating gear.

an oil dash-pot to take up the momentum of the moving parts at the end of the opening stroke. The mechanism by means of which the contacts are actuated is housed inside the top

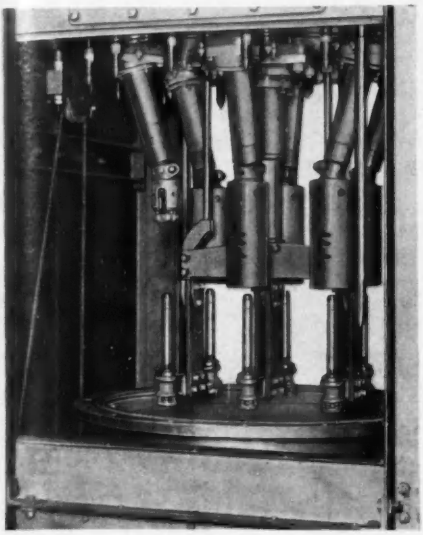


Fig. 3.—Interior of the circuit breaker shown in fig. 2.

plate. To prevent rotation of the contact cross-bar, two guide rods are provided which are attached to the under side of the top plate.

THREE-TANK CIRCUIT BREAKERS.

The general construction of each phase of the three-tank breaker is similar to that of the single-tank type. Three separate top plates are provided, each being of somewhat elongated rectangular form (fig. 4), and these are mounted on a channel iron frame, together with the operating mechanism box. Accommodation is provided in each top plate for the current transformers and phase operating mechanism, while the construction of the supports for the bushings is as described above.

The circuit breaker tanks are of flat rectangular construction, the width at the bottom being reduced so that the side view of the tank is trapezoidal. The object of this is to reduce the oil content as far as possible, to reduce the overall weight of the unit and to contribute to the ease with which individual tanks can be handled. If desired, oil filling and drainage cocks may be fitted to the tanks; oil gauges can also be provided. The tanks are lined with high quality resin impregnated boards capable of withstanding full voltage to earth. Where there is any danger of the hot gas discharge from the arc control pots scorching these linings, they are protected by easily replaceable plywood screens.

Access to the circuit breaker contacts is obtained by lowering the tanks, without emptying the oil, for which a simple form of lowering gear is provided. This consists of a winch and two wire ropes passing over pulleys on the fixed structure. By looping these ropes under pulleys attached to the tank of the phase which it is desired to inspect, the tank may be lowered, and easy access to the contacts obtained. The winch consists of a nut running on a lead screw; it is thus automatically non-reversing and all danger of a tank running down of its own accord is avoided.

In general, the circuit breaker arcing contacts, which are contained in the arc control pots, serve also for carrying the

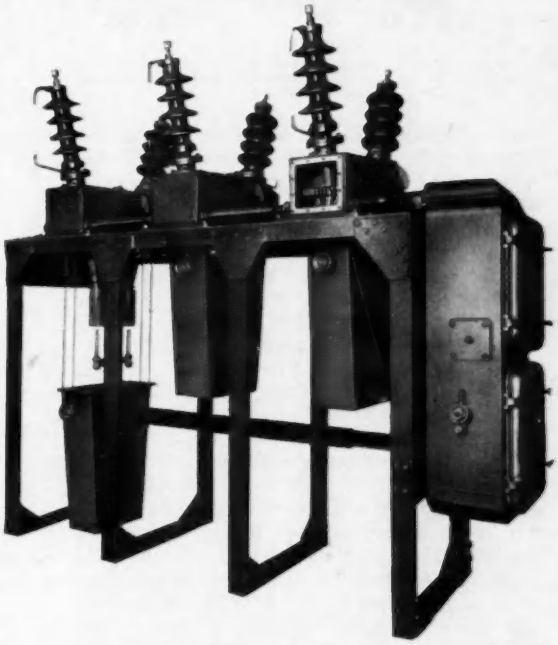


Fig. 4.—Three-phase three-tank 33 kV 750 MVA low-oil-content circuit breaker

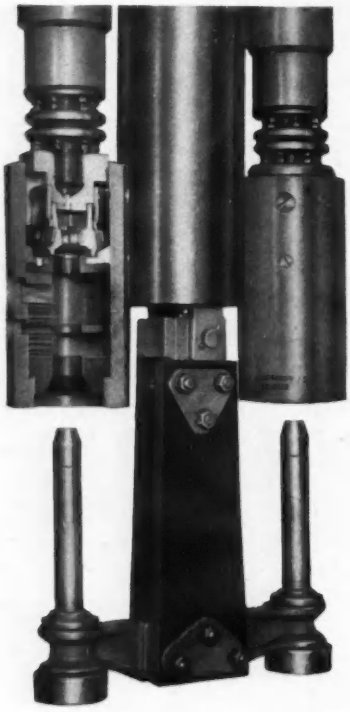


Fig. 5.—33 kV arc control pot cut away to show its internal construction.

main current. Fig. 5 shows a typical arc control pot cut open in order to reveal the construction of the pot and the arrangement of the contacts. The pot consists of a housing of special resin impregnated fabric, the lower end of which is closed by a resin impregnated paper plug, having a central hole for the entry of the moving contact. Lateral vents in the housing and stacks of fibre plates form a series of chambers and apertures which control and extinguish the arc in a uniform manner at all ratings. The fixed contacts in each pot consist of four spring-loaded copper fingers, while the moving contact consists of a solid copper rod with a removable tip of G.E.C. heavy alloy. Both the fixed contact fingers and the moving contact tip may be removed and replaced without any danger of altering the contact setting. The arc control pots may be removed merely by releasing four screws, as shown in fig. 6. This illustrates also the removal of a moving contact tip by means of two special ring spanners provided in the kit of tools.

The moving contacts are carried by a cross-bar consisting of a special copper alloy casting which is supported by insulators consisting of plates of synthetic resin impregnated paper. These plates are bolted to a block which is carried at the end of a tube which slides inside a fixed tubular guide and serves as a dashpot, as is shown by fig. 6.

The drive to the contacts is taken from the block through a swinging link to a lever mounted on the main operating shaft. The guides and links are shrouded by means of a varnish impregnated paper tube.

The drive from the operating mechanism to the three phases is effected by means of pull rods operating in steel tubes running between the individual top plates.

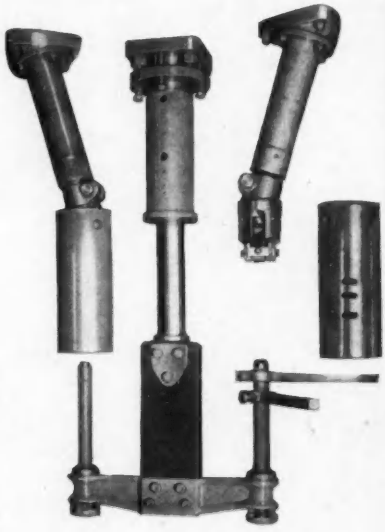


Fig. 6.—Interior of one phase of 33 kV oil circuit breaker; the arc control pot of one contact has been removed and the special spanners fitted for removing the moving contact tip.

BUSHINGS.

The dimensions and design of the bushings may to some extent be varied according to the user's requirements and the situation or climate in which the breaker is to be installed. The normal type consists of a bakelised paper condenser bushing, the lower end of which is carried down into the breaker tank and forms the support of the fixed contact and arc control pot.

The block to which the contacts are attached

is keyed and clamped to the paper of the bushing in order that the mechanical forces during operation are correctly transferred to the paper.

The upper end of the condenser bushing is protected by a porcelain weather shield, the narrow space between bushing and shield being filled with compound. In some situations special fog type porcelain shrouds may be required ; in other cases it may be advisable to use an oil filling between the bushing and the shroud. Suitable arcing horns can also be fitted.

66 kV CIRCUIT BREAKERS.

The 66 kV breaker is made only in the three-tank type; a typical breaker being shown in fig. 7. The general construction and appearance are very similar to those of the 33 kV breakers. The main difference is in the moving contacts which in the 66 kV breaker consist of a copper rod bent into a U shape, so that the contacts and cross-bar are all in one piece (fig. 8). This copper rod is held at the middle by a steel block which is shrunk on and pinned to the copper.

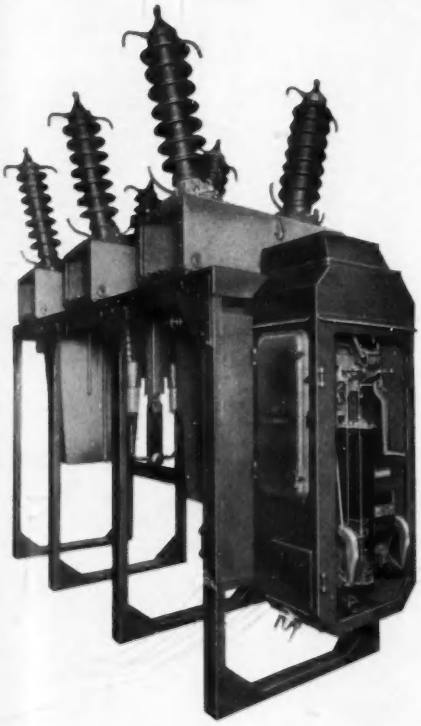


Fig. 7.—66 kV 750 MVA outdoor type low-oil-content circuit breaker with hand-wound spring operating gear. The tank has been removed from one phase to show the contacts.

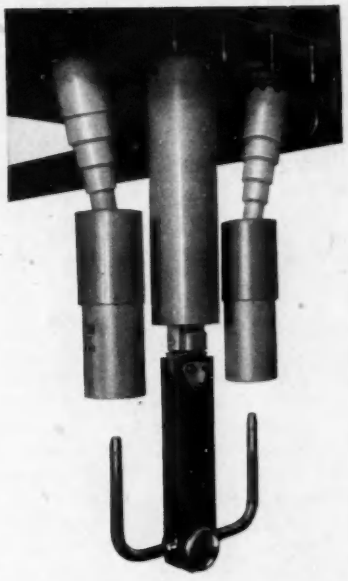


Fig. 8.—Moving contacts and arc control pots of the breaker shown by fig. 7.

This block contains holes through which pass the clamping screws by which the block is fastened to the insulators. The usual replaceable tips are fitted as in the 33 kV breakers.

In designing the current carrying parts, care has been taken to avoid sharp corners or projections that would lead to concentrations of electric stress. The fixed contacts are surrounded by a cylindrical stress shield (shown dismounted in fig. 9) which in turn is surrounded by a bakelised paper insulating shroud. The moving contacts are by their construction free from projections ; the ends of the bolts by which the contact is clamped to its supporting insulators are covered by domed stress shields, fig. 9.

OPERATING MECHANISMS.

All the standard types of G.E.C. operating mechanism may be supplied with these breakers, as, for example, direct-current solenoid, hand-wound spring operation or motor-wound spring operation.

The mechanisms are accommodated in weatherproof fabricated steel housings, with weathertight doors and internal heaters; ample ventilation is afforded.

Fig. 10 shows a solenoid operating mechanism suitable for a 33 kV breaker, while fig. 11

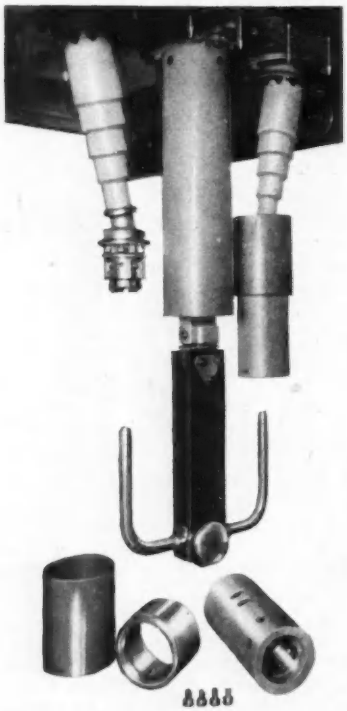


Fig. 9.—The contacts shown in fig. 7 after removing one arc control pot, together with the fixed contact, stress shield and insulating shroud.

shows a hand-wound spring operating mechanism suitable for a 66 kV breaker. This mechanism is so arranged that the springs may be charged, the breaker closed by releasing the springs, and the springs then recharged so as to be ready for a second closing operation as soon as the breaker has been tripped.

CONCLUSION.

The principal features which distinguish this range of circuit breakers are :

(1) The great robustness, simplicity and accessibility of the circuit breaker contacts and mechanism.
(2) Moderate dimensions and convenience of installation.
(3) The low oil content and the ease with which the oil may be handled.
(4) Ability to inspect the contacts without removing the oil or dismantling any parts of the breaker.
(5) High speed and reliability of operation.

These circuit breakers challenge comparison with the type in which a reduced oil content is achieved by abandoning an earthed metal tank and using a porcelain tube as an oil container. Such a comparison under any of the five heads above will show an advantage for the earthed tank design.

A steel tank is unquestionably more robust than a porcelain tank, the latter usually having to be reinforced internally with a paper tube in order to withstand internal pressure. The construction of the breakers described could hardly be simpler, as the number of separate parts has been reduced to the minimum consistent with adequate operation.

One of the main disadvantages of the live tank breaker is that it contains no bushings and hence no accommodation for current transformers. In consequence, these have to

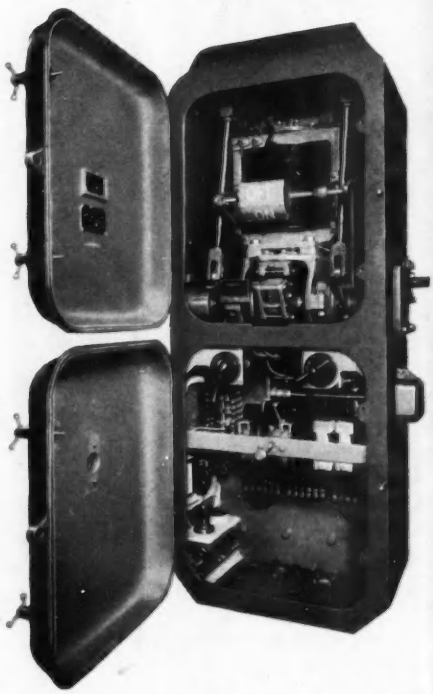


Fig. 10.—Circuit breaker operating mechanism box with solenoid operating mechanism, auxiliary switches, local operating controller and remote/local changeover switch, auxiliary wiring terminals and mounting for heater.

be housed either in a separate oil filled porcelain container or on a double-ended bushing specially provided for the purpose. It will therefore usually be found that a breaker such as is described in this article occupies less space in a substation than a live tank breaker if both are mounted at a convenient height for access, because the live tank breaker generally has to be provided with protective screening. If separately mounted current transformers are used, the comparison is even more in favour of the earthed tank breaker.

Fig. 11.—Hand-wound spring operating gear for 66 kV circuit breaker. The auxiliary switches and connections are accessible by the door on the left hand side of the box.

If, in order to avoid the necessity for screening, the live tank breaker is mounted at such a height that the lowest live metal is at a safe distance from the ground, access is made difficult as all operations on the breaker must be made from a ladder or portable platform. It not infrequently happens that current transformers must be mounted on both sides of the circuit breakers as, for instance, for some busbar zone protection schemes and in mesh type stations. In such cases the convenience of being able to mount the transformers on the bushings is very obvious ; equally obvious is the disadvantage of having to provide two sets of separate current transformer housings which would be required with a live tank breaker.

As a further comparison, the total oil content of a live tank circuit breaker and the associated oil-filled current transformers will, in general, be found to be greater than the corresponding amount required with the earthed tank breaker and current transformers. Moreover, if the current transformers of a live tank breaker are housed on special bushings, it usually happens that owing to the great overall length of such bushings, which must include two outdoor type weather shields as well as the axial length of the current transformers and their housing, difficulty is experienced in accommodating them and often necessitates increasing the size of the substation.

As regards ease of maintenance, the advantage is undeniably with the earthed tank low-oil-content type of breaker, as the removal of the tank is quite a simple matter which does not involve emptying the oil. Breakers of the live tank type must generally be partially dismantled for inspection of the contacts which, in any case, are all too frequently difficult of access. The need for running off the oil before the breaker can be opened is a further disadvantage, as it requires the use of hoses which are temporarily connected to the breaker while the inspection is in progress.

The Bright Annealing of Copper.

By IVOR JENKINS, M.Sc. and the late S. V. WILLIAMS, B.Sc.,

G.E.C. Research Laboratories.

INTRODUCTION.

COPPER was one of the first metals to be bright annealed on a commercial scale. Most of the early processes were based on the use of steam to prevent oxidation of the metal during the heat-treatment cycle and a number of ingenious furnaces were designed and used for this purpose. Continuous[1] and batch type furnaces were used and, in general, they were provided with water seals through which the copper was passed as it entered and left the furnace. The use of a water seal at the discharge end of the furnace had one advantage in that it accelerated the cooling of the copper and thus considerably reduced the length of the overall annealing cycle and in the case of continuous furnaces obviated the necessity for long cooling zones. On the other hand, the copper discharged from the furnaces was invariably wet and often stained. Thus although the material was bright annealed in the sense that there was little or no actual high temperature oxidation, it did not have the bright lustrous finish of cold rolled strip or drawn wire.

With the development and more general use of controlled atmospheres for the bright annealing of various metals and alloys, copper was one of the first applications to be studied, since it was generally agreed that a process which delivered bright annealed material in a dry condition was not only essential for some purposes, but was generally preferable to the older processes.

CHOICE OF ATMOSPHERE.

Compared with, say, ferrous materials, where the choice of a controlled atmosphere for heat-treatment is governed by various

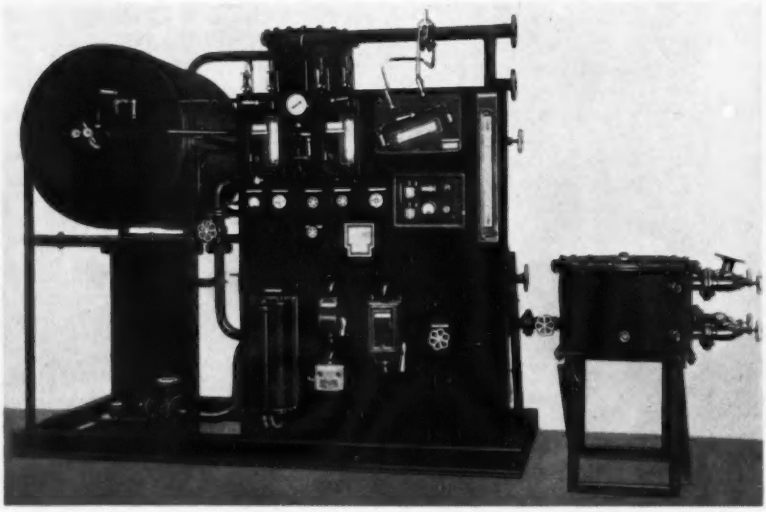


Fig. 1.—Regenerative ammonia burner. Nominal capacity 30 cu. metres per hour.
(Reproduced by the courtesy of I.C.I., Ltd., Billingham Division).

inter-gas and gas-metal reactions, the choice of an atmosphere suitable for copper is a comparatively simple matter, but even so any non-oxidising atmosphere cannot be used indiscriminately. The main requirements are freedom from oxygen and sulphurous gases and when annealing tough pitch copper the hydrogen content of the atmosphere is also important. Of the various atmospheres[2] which have been developed for bright annealing, burnt ammonia and burnt town's gas are the two which have been used to any appreciable extent for the bright annealing of copper, and it is proposed to consider these from the point of view of the three considerations mentioned above.

OXYGEN.

Burnt ammonia and burnt town's gas are, as their names imply, combustion products of ammonia and town's gas respectively and consequently, unless the combustion conditions are carefully controlled, the resultant atmospheres will contain free oxygen. Modern burners, both for ammonia and town's gas (figs. 1 and 2), are carefully designed with this specific object in view and trouble due to the presence of free oxygen should arise only when conditions are such that complete combustion of the raw gases is approached or attained. In practice such conditions are usually avoided in so far that the burners are operated so that the resultant atmospheres contain at least a low percentage of hydrogen.

The actual oxygen content of the bright annealing atmospheres, however, cannot be discussed without reference to the particular type of annealing furnace used. Thus a furnace which permits of more or less complete sealing during the cooling stage of the annealing cycle may, with a given atmosphere, produce perfectly bright copper. On the other hand the same atmosphere used in a furnace through which a flow of gas has to be maintained throughout the annealing cycle may result in oxidised or tarnished copper. The reason for this is that, in the first instance, any small amount of free oxygen is neutralised at the annealing temperature by the hydrogen (or carbon monoxide) in the atmosphere. When, however, it is necessary to maintain a flow of gas throughout the annealing cycle the copper will continue to be oxidised at temperatures below that at which the reducing gases present will reduce the oxide so formed. Thus with some types of annealing plant it is necessary to ensure that the atmosphere is absolutely free from oxygen, and for this purpose advantage is taken of the ease with which copper is oxidised. The gas, en route

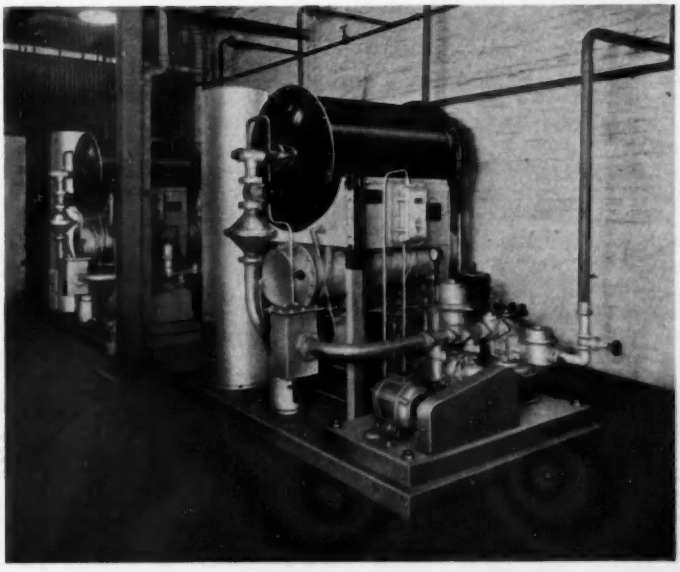


Fig. 2.—Town's gas burner with desulphurising towers. Nominal capacity 1000 cu. ft. per hour of burnt gas.

from the burner, is passed over copper heated to 600/700 degs. C. Any oxygen in the gas reacts with the copper to produce copper oxide which in turn reacts with the reducing gases present, with the formation of water vapour (or carbon dioxide), which is not detrimental so far as the copper in the annealing furnace is concerned.

On theoretical grounds, steam would be expected to oxidise copper at temperatures as low as 100 degs. C. but, as evidenced by the original steam process, the reaction is too slow to have any practical significance.

Similarly with carbon dioxide (CO_2), which is a constituent of burnt town's gas, oxidation of copper does not take place at least below 600 degs. C, which is the highest temperature normally encountered in the annealing of copper.

SULPHUROUS GASES.

Of the two atmospheres in general use for the annealing of copper, burnt ammonia is a simple mixture of hydrogen and nitrogen in proportions determined by combustion conditions, by virtue of the fact that, prior to dissociation and combustion, the original gas (anhydrous ammonia) is a very pure chemical compound. Water vapour, which is produced during the combustion, is partially or completely removed by condensers and the use of suitable dehydrating agents.

The atmosphere as delivered to the annealing furnace is free from sulphurous compounds which have a very deleterious effect on copper.

In the case of burnt town's gas, however, this freedom from sulphurous compounds does not exist and steps have to be taken to remove these impurities before the gas is used for bright annealing copper. Sulphurous gases may be present in burnt town's gas as hydrogen sulphide (H_2S), sulphur dioxide (SO_2) and organic sulphur compounds (COS, CS_2). Of these, H_2S is the most important, since it rapidly attacks copper with the production of a black film of copper sulphide which is removed only with difficulty and usually by a dilute alkali cyanide solution. Thus complete absence of H_2S is essential if bright annealed copper is to be produced.

Sulphur dioxide (SO_2) on the other hand is practically inert to copper up to ordinary annealing temperatures and can be tolerated in a dry hydrogen-free atmosphere. In the presence of hydrogen a reaction—catalysed, for example, by the steel heat-treatment container—may take place as follows :—

$$SO_2 + 3H_2 \rightleftharpoons H_2S + 2H_2O \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

Most, if not all, of the SO_2 produced during the combustion of town's gas, however, is removed by solution in the condenser of the burner unit, and in practice no special precautions are necessary with respect to this particular gas.

Organic sulphur compounds such as carbon oxysulphide (COS) and carbon disulphide (CS_2) are also more or less inert to copper at normal annealing temperatures and do not give rise to staining. In the presence of a suitable catalyst, however, they also react with hydrogen to produce H_2S, as follows :—

$$COS + H_2 \rightleftharpoons CO + H_2S \cdot \quad \cdot \quad \cdot \quad (2)$$

$$CS_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2S \quad \cdot \quad \cdot \quad (3)$$

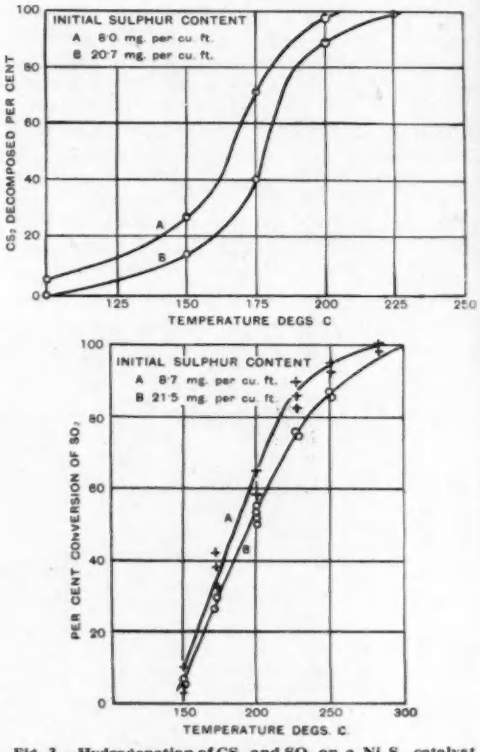

INITIAL SULPHUR CONTENT
A 8·0 mg. per cu. ft.
B 20·7 mg. per cu. ft.
CS₂ DECOMPOSED PER CENT
TEMPERATURE DEGS C
INITIAL SULPHUR CONTENT
A 8·7 mg. per cu. ft.
B 21·5 mg. per cu. ft.
PER CENT CONVERSION OF SO₂
TEMPERATURE DEGS. C

Fig. 3.—Hydrogenation of CS_2 and SO_2 on a Ni_3S_2 catalyst (Crawley & Griffith).

All the above reactions are reversible, and in the absence of H_2S quite low concentrations of hydrogen are sufficient to promote the formation of H_2S.

The nature in which the sulphur exists in burnt town's gas is to a large extent determined

by the ratio of air to town's gas used for combustion. Thus, when the gas is partially burnt at an air to gas ratio of 2 to 1, such as is normally used in low carbon steel annealing, the bulk of the sulphur is present in the burnt gas as hydrogen sulphide, with only approximately 5 per cent of the total present as the carbon oxysulphide. At ratios near to complete combustion, however, the sulphur is present more or less entirely as sulphur dioxide. Processes have been developed for the complete desulphurisation of the burnt town's gas, whether it is partially or completely combusted. Hitherto, the most generally accepted process has been based on that developed by the Gas Light & Coke Company,[3] whereby the sulphur is removed in two stages. First, the burnt gas is passed through the conventional type of iron oxide purifier, whereby the hydrogen sulphide in the gas is completely absorbed. The organic sulphur and/or sulphur dioxide remaining in the gas are then converted to hydrogen sulphide, according to reactions (1)–(3), by passing the gas over a special catalyst, nickel subsulphide (Ni_3S_2), maintained at approximately 200 degs. C. The hydrogenation of the sulphur compounds results in the formation of hydrogen sulphide which is absorbed

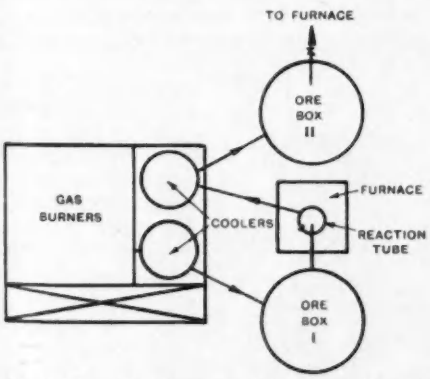


Fig. 4.—Town's gas burner with desulphurising unit including catalyst tube.

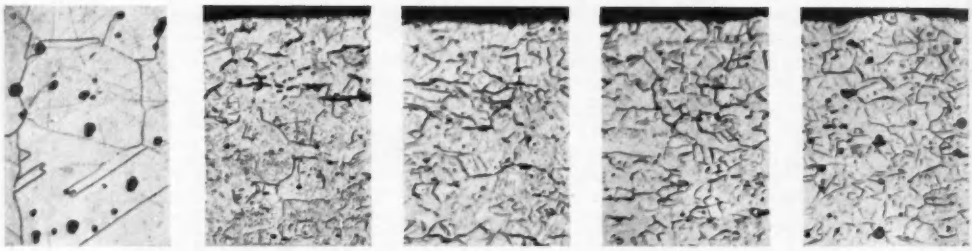
in a second iron oxide purifier. Curves for the conversion of carbon disulphide and sulphur dioxide, according to Crawley & Griffith,[4] are shown in fig. 3. Complete hydrogenation can be obtained without difficulty. It has been found in practice that the conversion of the organic sulphur in the absence of hydrogen sulphide can be obtained equally effectively by passing the gas through a hot furnace tube filled with, for example, crushed refractory maintained at approximately 850 degs. C. Fig. 4 shows a schematic arrangement of a town's gas burner complete with iron oxide towers and reheating furnace. An alternative method of desulphurising burnt town's gas is to pass the gas through a bed of activated carbon which has the property of physically adsorbing all the sulphur compounds present. The process is simple to operate and it is usual to work with two adsorption chambers in series. The activated carbon can be regenerated by heating in steam, a process which is usually done by the suppliers who have special equipment for the purpose.

By the adoption of one of the desulphurising processes mentioned, burnt town's gas may be rendered quite suitable, and is extensively used for the bright annealing of copper.

It is possible for copper, annealed in burnt ammonia or completely desulphurised burnt town's gas, to be sulphur-stained due to the decomposition inside the annealing container of sulphur-containing lubricants introduced with the charge. In continuous furnaces it is always advisable to ensure that the flow of gas is directed over the hot copper towards the charging end, thereby reducing the possibility of the oil vapours decomposing at the higher furnace temperatures. In batch type furnaces the flow of gas through the container should be sufficient to sweep away the oil vapours more or less as quickly as they are formed. The nature of the charge, however, may be such that the oil vapours are not removed quickly, as, for example, in the treatment of copper strip in coils. If the removal of oil vapour trapped in this way is unduly delayed, the temperature of the work and of the container may be such that decomposition of the vapours takes place. The decomposition of oil vapours in this way invariably results in the direct or indirect formation of hydrogen sulphide, which, of course, stains the copper. Complete degreasing of the material before annealing is one solution of the problem, but this frequently has to be dismissed on economic grounds. In recent years rolling oils of very low sulphur content have become available, but sulphur-staining from this source has not been eliminated completely.

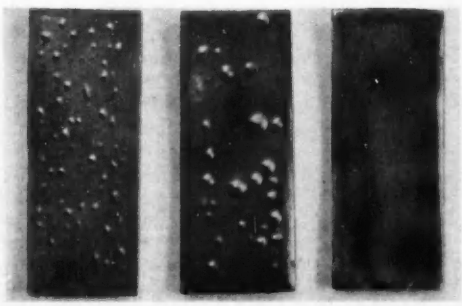
The decomposition or the reduction of organic sulphur compounds by hydrogen at temperatures normally employed for copper annealing has to be catalysed if it is to proceed to any great extent. Copper itself exerts no apparent catalytic effect and since, as already pointed out, organic sulphur compounds are relatively inert to the metal, they do not give

rise to staining even when present in atmospheres containing hydrogen. Thus, for example, it is possible to bright anneal copper strip in a silica tube furnace, in a burnt town's gas atmosphere containing organic sulphur, provided that it is free from hydrogen sulphide or sulphur dioxide. The concentration of hydrogen under such conditions can be at least as high as 15 per cent without sulphur-staining being produced. Iron, on the other hand, is a very active catalyst in promoting the reduction of sulphur dioxide and organic sulphur by hydrogen. It is not possible, therefore, to bright anneal copper in an iron or steel container in an atmosphere containing hydrogen plus either sulphur dioxide or organic sulphur, even in the absence of free hydrogen sulphide. The fact that copper does not catalyse the break-down of organic sulphur has, however, resulted in a recent development[5] which eliminates the possible harmful effects of oil vapours in the annealing container upon the surface condition of the annealed material. The whole of the interior of the annealing container is sprayed with copper, so that no ferrous surface is exposed to the furnace atmosphere. In this way, copper with surface films of sulphur-bearing rolling oils or other lubricants can be bright annealed as successfully as the degreased material. The annealing atmosphere used can be burnt town's gas containing sulphur, and the only sulphurous gas which need be removed before use is the hydrogen sulphide. Concentrations of sulphur dioxide and of organic sulphur such as are met with in the normal controlled atmosphere generated from town's gas, are quite harmless even in the presence of up to 8 per cent hydrogen. Aluminium sprayed on the inside of containers is equally as suitable as copper, from this point of view. The process has proved to be especially successful for the bright annealing of copper sheets and strip having a highly polished surface finish, but coated with a film of rolling oil which in the ordinary way gives rise to sulphide tarnishing, even in dissociated ammonia atmospheres.



(a) (b) (c) (d) (e)

Fig. 5.—Embrittlement of annealed copper containing 0.07 per cent oxygen. Magnification × 250.
(a) As cast showing oxide particles. (b) Annealed 500 degs. C. burnt town's gas containing 10 per cent H_2. (c) Annealed 500 degs. C. burnt town's gas containing 1 per cent H_2. (d) Annealed 450 degs. C. burnt town's gas containing 10 per cent. H_2. (e) Annealed 450 degs. C. burnt town's gas containing 1 per cent H_2.



(a) (b) (c)

Fig. 6.—Blisters formed on copper containing 0.24 per cent oxygen on heating in hydrogen at 850 degs. C., magnification 1.25. (a) 10 mms. pressure hydrogen. (b) 5 mms. pressure hydrogen. (c) 2 mms. pressure hydrogen.

HYDROGEN AND THE EMBRITTLEMENT OF COPPER.

Hydrogen is inert to pure copper, but its reaction on copper containing oxygen can give rise to very pronounced embrittlement. A substantial proportion of the copper produced in strip and wire form contains oxygen. The solid solubility of oxygen in copper is very low, being of the order of 0·01 per cent to 0·007 per cent within the temperature range of 950/650 degs. C. The oxygen is therefore mainly present as a precipitated oxide which coalesces fairly rapidly at elevated temperatures. Ransley[6] has investigated the deoxidation of such material when heated in hydrogen or carbon monoxide, and his work has thrown much light on the mechanism of

embrittlement. Deoxidation in carbon monoxide is analogous to the decarburisation of a carbon steel in water vapour, for example, in that the reaction is confined to the surface of the material, since the molecules of carbon monoxide do not diffuse into the solid metal. De-oxidation in hydrogen, on the other hand, is complicated by the fact that the hydrogen itself is capable of diffusion into the solid metal. As the de-oxidation of the copper proceeds, the rate of arrival of oxygen atoms at the surface of the metal becomes insufficient to satisfy the concentration of hydrogen at the surface, with the result that the hydrogen diffuses into the metal. The hydrogen reduces the oxide in the body of the metal with the formation of water vapour, at a pressure sufficient to cause internal rupturing and blistering of the copper (figs. 5 and 6).

It is apparent, therefore, that the heat treatment in controlled atmospheres of copper containing oxygen must be carefully carried out to ensure that embrittlement is not obtained. If hydrogen is not present in the annealing atmosphere and is not produced within the furnace chamber, then the problem of embrittlement does not arise. Thus, for example, pure carbon monoxide will eventually completely de-oxidise copper without giving rise to any embrittlement whatsoever, but in the presence of water vapour, however, the formation of hydrogen is promoted, according to the following reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \cdot \quad \cdot \quad \cdot \quad (4)$$

The hydrogen thus produced may result in embrittlement of oxygen-containing copper. In point of fact the embrittling effect of hydrogen is far more marked in an atmosphere containing carbon monoxide than when the latter gas is absent. This is due to the fact that the oxygen arriving at the surface of the copper by diffusion is reduced solely, or at least in the greater part, by the carbon monoxide. The hydrogen is thus available in almost its maximum concentration for diffusion into the solid metal.

It is also interesting to note that embrittlement of copper containing oxygen can result from annealing in steam, due to the formation inside the annealing container of hydrogen produced by the reaction of the steam with the iron of the container.

$$Fe + H_2O \rightleftharpoons FeO + H_2 \quad \cdot \quad \cdot \quad \cdot \quad (5)$$

The embrittling action of hydrogen is a function of the rate of diffusion of the gas into copper, and this in turn is a function of temperature, and in practice embrittlement

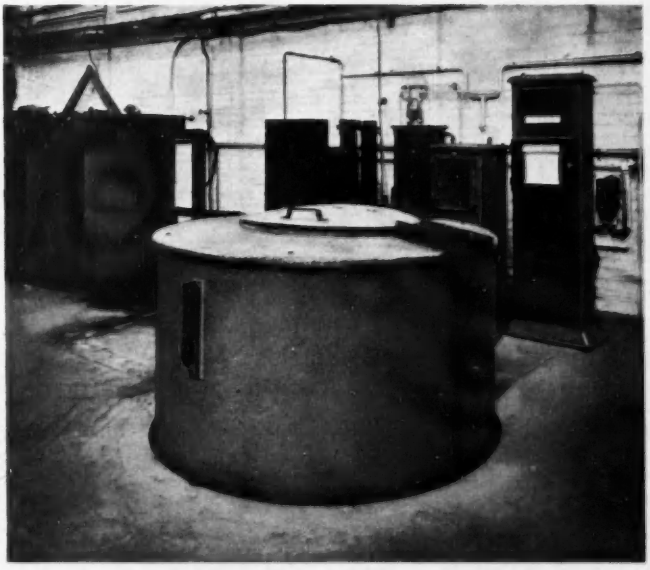


Fig. 7.—Vertical cylindrical bright annealing plant for copper strip in coils, showing town's gas burner in background.

is not serious at temperatures below 450 degs. C. Thus, when annealing copper at temperatures below 450 deg. C. it is possible to use a controlled atmosphere containing up to 10 per cent of hydrogen and carbon monoxide. In the ordinary way, commercial annealing temperatures for copper are below 450 degs. C, but if for any reason it is desired to exceed this temperature the hydrogen content of burnt ammonia should not exceed about 0·5 per cent, and in the case of de-sulphurised burnt town's gas, the combined hydrogen and carbon monoxide content should be less than 1 per cent. It is necessary to specify the carbon monoxide content because of the possibility of the formation of hydrogen according to reaction (4) above.

PRACTICAL APPLICATIONS.

Cold rolled copper strip is usually bright annealed in coils in batch type furnaces. Both the vertical cylindrical pot furnace and the bell type furnace are used for this purpose. Of these, the former offers certain advantages in so far that by the use of a water-cooled ring it is possible to maintain a really gas-tight closure, and it is unnecessary to have a flow of gas through the pot during the cooling stage of the heat-treatment cycle. With bell type furnaces the seal is not so positive, and a flow of gas has to be maintained throughout the annealing cycle. The significance of this difference has already been considered in connection with the effect of traces of free oxygen in the controlled atmosphere, and it is not unusual to find, on bell-furnace installations, that it is necessary to interpose a reheater between the gas burner and furnace for the removal of all traces of free oxygen. A vertical cylindrical pot furnace installation for the bright annealing of copper strip in coils is shown in fig. 7, the controlled atmosphere being burnt town's gas.

The furnace pots can be readily sprayed internally with copper or aluminium, with a view to preventing the hydrogenation of organic sulphur compounds which may be introduced into or formed inside the pot.

Continuous furnaces with controlled atmospheres are not in general use for the bright annealing of copper strip. Copper wire and parts such as pressings, etc., are annealed continuously, the latter usually in continuous belt type furnaces. In the case of fine copper wire, single strand multi-tube furnaces are sometimes used. The controlled atmosphere is supplied to each tube from a manifold distributor, and if combustible is allowed to burn at the entrance end only.

The copper brazing of steel parts in controlled atmospheres may be considered as a special case where it is essential to prevent oxidation of the copper if sound joints are to be produced. Since in this particular application the question of hydrogen embrittlement of the copper does not arise, atmospheres with higher hydrogen contents can be used and, in fact, are preferable, since the higher hydrogen content ensures freedom from oxidation which is essential if the copper is to run into the joint. The actual choice of atmosphere is to a certain extent determined by the steel being brazed ; thus certain alloy steels demand the use of a pure highly reducing gas such as hydrogen or cracked ammonia. Mild steel parts on the other hand can be satisfactorily copper brazed in burnt ammonia or de-sulphurised burnt town's gas, whereas in the case of high carbon steel parts, precautions have to be taken to avoid de-carburisation.

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Deflected Beam Valves for Ultra High Frequencies.

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Research Staff of the G.E.C. and M.O. Valve Co.

The theory of transverse control of an electron beam is investigated at frequencies where the electron transit times are comparable with the period of the alternating field. Expressions are derived for the high frequency mutual conductance and input resistance. Some examples of valves designed for frequencies up to 750 megacycles per second are mentioned.

1. INTRODUCTION.

SINCE the earliest days of the thermionic valve, many attempts have been made to utilise the transverse deflection of an electron beam by an alternating voltage in order to amplify that voltage.[1, 2] The results in most cases proved inferior to those obtained by density control of the electronic current by means of a grid. However, the advent of very high frequencies has revealed the limitations of space charge control and several writers have advocated the use of deflection control which would appear to have certain advantages.

In the early days of the war a programme of work was undertaken at the Laboratories to investigate the possibility of using beam deflection valves as amplifiers, frequency changers and oscillators for short wave radar receivers. One advantage appeared to be the possibility of designing such valves without having to employ very small inter-electrode spacings necessary in short wave triodes and pentodes, requiring extreme accuracy in components and skill in assembly.

At the time this article was originally written* much had already been published on the subject (see references 3—13), and although most of the writers were agreed on the suitability of deflection valves for high frequency operation, there was some difference of opinion on the theoretical results, particularly with reference to the input impedance of such valves. There is a greater measure of agreement in more recent publications[14, 15] but there still appear to be some doubts[16] which the authors of the present article feel are due to lack of appreciation of the fundamental mechanism in the conversion of power from D.C. to A.C.

In the present article the authors derive a general expression for the high frequency sensitivity of deflection control valves, and from considerations of the energy of the electrons, calculate the input resistance. In the analysis of this latter problem an attempt is made to give as clear a picture as possible of the transfer of energy between the input circuit and the electrons. It is shown that both in sensitivity and in input resistance deflection control valves compare favourably with grid control valves at high frequencies, although experimental work led to the conclusion that shot noise associated with the electron beam and with the division of current between the anodes makes valves of this type inferior to modern high frequency triodes as amplifiers of very small signals.

2. DEFLECTION SENSITIVITY AT ZERO FREQUENCY.

The type of system considered is shown in plan in fig. 1. A planar beam of electrons, A, is shot between two deflecting plates, B and C. When the plates are at the same potential the beam current is divided equally between two collecting anodes, D and E. When a small potential difference is applied between B and C, then, if the portion of the beam which is transferred from one anode to the other has uniform current density, the difference of the currents to the two anodes is proportional to the potential difference. The relation between the anode current and the deflecting potential

* This article was originally written in 1941, but publication was not then allowed.

1. LIST OF SYMBOLS.

x	= transverse co-ordinate.	r	$= \tau_2/\tau_1$
y	= longitudinal co-ordinate.	I	= total beam current.
$\dot{x}$, $\ddot{x}$	= transverse components of electron velocity and acceleration respectively.	C_o	= deflection sensitivity at zero frequency.
$\dot{y}$	= longitudinal component of electron velocity.	C	= deflection sensitivity at high frequency.
e	= charge of an electron.	ω	= angular frequency.
m	= mass of an electron.	v	= potential difference between the deflecting plates.
a	= distance between the deflecting plates.	g_{m_o}	= mutual conductance of the deflecting plates at zero frequency.
d	= width of the electron beam.	g_m	= mutual conductance of the deflecting plates at high frequency.
t	= instantaneous time.	V	= potential at a point in the deflecting field.
t_o	= time of arrival of an electron at the deflecting system.	V_o	= mean potential of the field.
τ	= time of transit of an electron measured from t_o	u	= total velocity of an electron.
τ_1	= time of transit of an electron in the deflecting system.	R	= input resistance of the deflecting system.
τ_2	= time of transit of an electron from the deflecting plates to the anodes.	g	$= 1/R$ = input conductance of the deflecting system.

difference for an actual valve is shown in fig. 2. It can be seen that over quite a large part of the characteristic the anode current is proportional to the deflecting potential difference.

The mean potential of the deflecting plates is assumed to be equal to the space potential, which is constant throughout the system. Under these conditions the electrons move along the y-axis with uniform velocity (fig. 3).

When a small potential difference is applied between the deflecting plates, their mean potential being unchanged, there is a force acting on the electrons and the equation of transverse motion of one electron is

$$m\ddot{x} = \frac{ev}{a}$$

Integration of this equation gives for the velocity and displacement at the end of the deflecting plates

$$\dot{x} = \frac{ev}{ma}\tau_1 \text{ and } x = \frac{ev}{2ma}\tau_1^2$$

x and $\dot{x}$ are assumed to be zero on entering the deflecting plates at time t_o where $\tau = t - t_o$.

If it now be assumed that the electron enters field free space on leaving the deflecting plates and continues to move with constant longitudinal and transverse velocities then the deflection of the electron at the anode is given by

$$C_o = \frac{ev\tau_1}{2ma}\left(\tau_1 + 2\tau_2\right) \quad \cdot \quad \cdot \quad (1)$$

The effect of the fringing field at the ends of the deflecting system has been neglected in deriving equation (1), an assumption which is justified if the transit time through the fringing field is small compared with τ_1, and it has been assumed that the longitudinal velocity of the

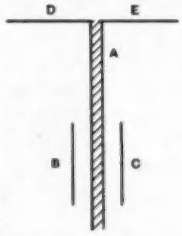

Fig. 1.—Section of the system showing the deflecting plates (B, C,) the anodes (D, E,) and the electron beam (A).

electron remains constant throughout. Actually this latter assumption is not strictly correct as is shown in section 5. However, for small deflections the error is small and equation (1) gives the deflection sensitivity of the system.

Since C_o is proportional to the square of the transit time in the deflecting plates it is desirable to make this transit time as large as possible.

For the double anode system of fig. 1, the mutual conductance of the deflecting plates is given by

$$g_{m_o} = \frac{C_o I}{d v}$$

It is assumed that d is small compared with

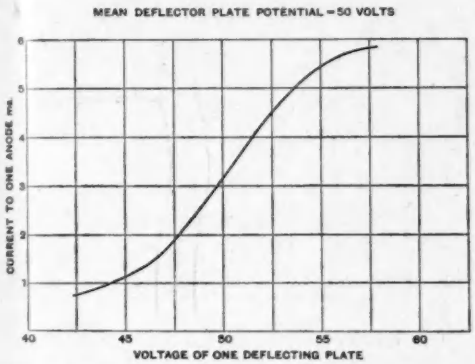

Fig. 2.—Variation of the anode current with deflection plate voltage.

a so that all the electrons have similar paths. Substitution from equation (1) gives

$$g_{m_o} = \frac{9\times10^{14}.\ \tau_1(\tau_1+2\tau_2)\ I}{a\ d} \text{ amps/volts} \quad (2)$$

It has been assumed in the foregoing analysis that the mean potential over a cycle of the whole of the space traversed by the electrons is constant. The argument, however, is also valid when there is an accelerating or decelerating field in the space between the deflectors and the anodes, provided this field does not produce any transverse focusing fields in the paths of the beam. Such a condition can be realised, for example, if there is placed between the deflectors and the anodes a transverse screen at the potential of the deflectors. The mean anode potential may then be higher or lower than the deflector potential without affecting the validity of equations (1) and (2). In general, however, if the anode and deflector potentials are not the same, focusing or defocusing fields will decrease or increase both the deflection sensitivity, C_o, and the width of the beam, d, at the point where it divides between the two anodes. To some extent the effects on deflection sensitivity and beam width are mutually compensating but experience shows that in general the beam width at the anode changes more rapidly than C_o with the result that the mutual conductance can be increased by focusing the beam to a narrow cross section. By a suitable design and choice of electrode potentials it has been possible to obtain a mutual conductance of 4 - 5 mA/V with a cathode current of about 4 mA.

3. DEFLECTION SENSITIVITY AT HIGH FREQUENCIES.

With a small alternating potential on the deflecting plates the equation of motion of an electron and its integrals are

$$m\ddot{x} = \frac{e v \cos\omega t}{a}$$

$$\dot{x} = \frac{e v}{ma\omega}\left(\sin\omega t - \sin\omega t_o\right) \quad \cdot\ \cdot \quad (3)$$

and

$$x = \frac{e v}{ma\omega^2}\left\{-(\cos\omega t - \cos\omega t_o) - \omega(t-t_o)\sin\omega t_o\right\} \quad (4)$$

At the end of the deflecting plates the velocity and the displacement are given by

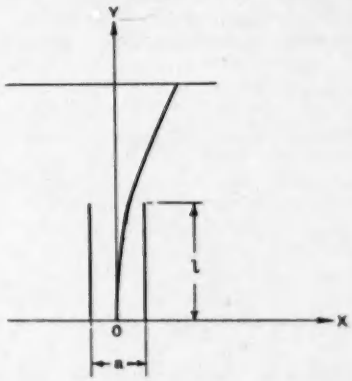

Fig. 3.—Path of one electron for a steady potential difference between the deflecting plates.

$$\left(\dot{x}\right)_{\tau_1} = \frac{2e v}{ma\omega}\cos\omega\left(t_o + \frac{\tau_1}{2}\right)\sin\frac{\omega\tau_1}{2}$$

and

$$\left(x\right)_{\tau_1} = \frac{e v}{ma\omega^2}\left\{2\sin\omega\left(t_o+\frac{\tau_1}{2}\right)\sin\frac{\omega\tau_1}{2} - \omega\tau_1\sin\omega t_o\right\}$$

The horizontal displacement at the anode is now

$$X = \left(x\right)_{\tau_1} + \tau_2\left(\dot{x}\right)_{\tau_1}$$

$$= \sin\omega t_o \left\{\frac{ev}{ma\omega^2}\left(\sin\omega\tau_1 - \omega\tau_1\right) + \frac{ev\tau_2}{ma\omega}\left(\cos\omega\tau_1 - 1\right)\right\}$$

$$+ \cos\omega t_o \left\{\frac{ev}{ma\omega^2}\left(1 - \cos\omega\tau_1\right) + \frac{ev\tau_2}{ma\omega}\sin\omega\tau_1\right\}$$

This can be expressed in the form

$$X = C\cos\left(\omega t_o + \alpha\right) \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (5)$$

where

$$C = \frac{ev}{ma\omega^2}\left[\left(\omega\tau_1\right)^2 + 2\left(1 - \cos\omega\tau_1\right)\left\{1 + \omega\tau_2\left(\omega\tau_1 + \omega\tau_2\right)\right\} - 2\omega\tau_1\sin\omega\tau_1\right]^{\frac{1}{2}} \quad \cdot \quad (6)$$

and

$$\alpha = \tan^{-1}\left\{\frac{\omega\tau_1 - \sin\omega\tau_1 + \omega\tau_2\left(1 - \cos\omega\tau_1\right)}{1 - \cos\omega\tau_1 + \omega\tau_2\sin\omega\tau_1}\right\} \quad (7)$$

The deflection at the anode is given by equations (5), (6) and (7). Equation (6) gives the amplitude of the deflection and equation (7) its phase measured from the time t_o, when the electron entered the deflecting space.

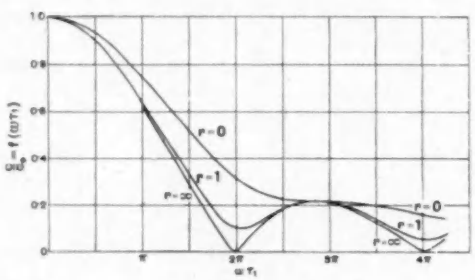

Fig. 4.—Variation of the ratio of H.F. sensitivity to L.F. sensitivity with transit angle.

The ratio of the high frequency sensitivity to the zero frequency sensitivity can be obtained from equations (1) and (6).

Thus, $C = C_o f\left(\omega\tau_1\right)$ for a fixed value of r where

$$f\left(\omega\tau_1\right) \equiv \frac{2}{\omega\tau_1}\cdot\frac{1}{1+2r}\left[1 + 2\left(1 - \cos\omega\tau_1\right)\left\{\frac{1}{\left(\omega\tau_1\right)^2} + r\left(1 + r\right)\right\} - \frac{2\sin\omega\tau_1}{\omega\tau_1}\right]^{\frac{1}{2}} \quad (8)$$

The function $f\left(\omega\tau_1\right)$ is plotted in fig. 4 for values of r of o, 1 and ∞. The first case gives the deflection sensitivity at the end of the deflecting space and the last is the sensitivity of a normal cathode ray tube. The other case with equal transit times is representative of the type of valve which appears most promising as a high frequency amplifier.

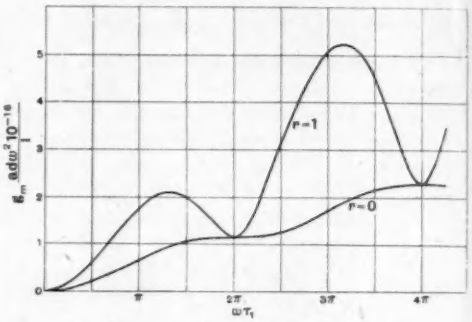

Fig. 5.—Variation in mutual conductance with transit angle at constant frequency.

The magnitude of the mutual conductance at high frequency can be determined from equation (6) in the form

$$g_m \cdot \frac{ad\omega^2 \times 10^{-16}}{I} = 0{\cdot}18\,\omega\tau_1\left[1 + 2\left(1 - \cos\omega\tau_1\right)\left\{\frac{1}{\left(\omega\tau_1\right)^2} + r\left(1 + r\right)\right\} - \frac{2\sin\omega\tau_1}{\omega\tau_1}\right]^{\frac{1}{2}} \quad (9)$$

$$= g\left(\omega\tau_1\right)$$

The function $g\left(\omega\tau_1\right)$ which is plotted in fig. 5, gives the variation of mutual conductance of a given valve at a fixed frequency when the transit time is varied.

It can be seen that, when the frequency is kept fixed, there are certain values of the transit angle which give maxima of sensitivity. Very large values of transit time may not be compatible with the focusing requirements of the beam but it should be possible particularly at the higher frequencies to utilise these maxima to improve sensitivity.

4. THE INPUT RESISTANCE OF THE DEFLECTING SYSTEM.

(a) Energy Considerations.

Before dealing with the high frequency case it is desirable to consider the interchange of energy between the electrons and the field at zero frequency. It is still assumed that the electrons move with constant longitudinal velocity in the deflecting space, and that they start with zero velocity at a point of zero

potential. Under these conditions the electrons arrive at the point O (fig. 6), with a velocity corresponding to the potential at that point, *i.e.*, the gain in kinetic energy, $\frac{1}{2} m\dot{y}^2$, is equal to the loss in potential energy, eV. In this figure the axes of co-ordinates represent the kinetic energy of an electron and longitudinal distance. The dotted line D represents the distance at which the electrons may be considered to be outside the field of the deflecting plates, *i.e.*, on the anode side of D there is field free space and between the deflecting plates and D there is the fringing field of the deflecting plates. The full line

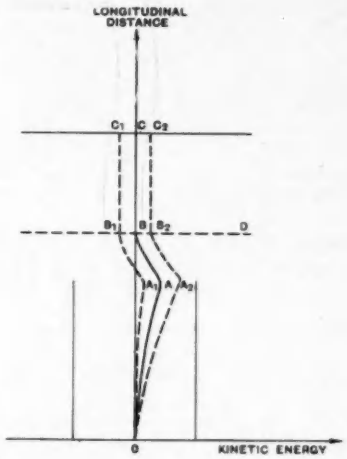

Fig. 6.—Variation of kinetic energy of electrons in passing through the deflectors to the anodes (see text)

O A B C shows the change of the kinetic energy of an electron during its transit through the deflecting plates to the anode. The electron acquires a transverse component of velocity as a result of the deflecting field. The total kinetic energy of the electron is given by

$$\frac{1}{2} m (\dot{x}^2 + \dot{y}^2)$$

and since the longitudinal velocity remains constant in the deflecting space, this means that the electron's kinetic energy increases. This increase in energy is supplied by the source of potential difference across the deflecting plates. At A the increase of kinetic energy is equal to its loss of potential energy in moving from the mean field potential to the higher potential of the point corresponding to A. In moving from this point to D which is at the mean field potential, the electron is decelerated and at B its kinetic energy is again equal to its initial value at O. Thus, during the transit of the deflecting plates, the electron increases its energy at the expense of the deflecting system, but in the passage from the deflecting system to D this energy is returned so that on the whole no energy is consumed from the deflecting system.

From D to the anode the electron moves with uniform velocity and energy. However, since the electron acquires a transverse component of velocity in the deflecting system, the longitudinal velocity beyond D must be diminished in order to keep the kinetic energy equal to its initial value at O. Thus, deflection is always accompanied by a reduction in forward velocity, as pointed out by Colebrook.[3]

In the zero frequency case just considered, the velocity and kinetic energy of the electron at any point in the field correspond to the value of the potential at that point throughout the whole transit.

Thus, if u is the total velocity of the electron at A and V is the potential, then

$$\frac{1}{2} m u^2 = eV \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (10)$$

If V_o is the potential at D the electron loses kinetic energy of amount $e(V - V_o)$ between A and B.

At high frequencies when the electron transit time is comparable with the period of the alternating field, it is well known that an electron may have a kinetic energy which does not equal its loss of potential energy. Thus the electron may reach the end of the deflecting system with potential energy eV but with a value of kinetic energy which differs from that given by equation (10). Two such cases are shown at A_1 and A_2 in fig. 6. In both cases the loss of kinetic energy in moving from the deflecting plates to D is given by $e(V - V_o)$ assuming that the transit time here is small compared with the period. Thus some electrons ultimately reach the anode with excess energy ($A_2B_2C_2$) and some with diminished energy ($A_1B_1C_1$). In the first case energy has been taken from the deflecting system and in the second case energy has been given to the deflecting system. In both cases the amount of energy taken by the electron from the deflecting system equals the excess of the kinetic over the loss of potential energy on emergence from the deflecting plates. The mean over a complete period of this excess for all the electrons gives the resultant loss of energy per cycle and this can be interpreted as a resistance across the deflecting plates.

These energy considerations have been given in detail because they show the actual

mechanism of the losses in the input circuit, and, as is shown later, they explain wherein the discrepancies in previous papers arise.

(b) Calculation of the Input Resistance.

From equation (3) the horizontal component of the velocity of an electron on emergence from the deflecting plates is

$$\dot{x} = \frac{e\,v}{ma\omega}\left\{\sin\omega\,(t_o + \tau_1) - \sin\omega t_o\right\}$$

and its kinetic energy is

$$K.E. = \tfrac{1}{2}\,m\,\dot{x}^2$$
$$= \frac{e^2v^2}{2ma^2\omega^2}\left\{1 - \cos\omega\tau_1 - \frac{\cos 2\omega t_o}{2} + \cos(2\omega t_o + \omega\tau_1) - \frac{\cos\,2\omega\,(t_o + \tau_1)}{2}\right\}$$

The potential energy of the electron on emergence from the deflecting plates is

$$P.E. = \frac{e\,x\,v}{a}\cos\omega\,(t_o + \tau_1)$$

Using equation (4) and simplifying, we get

$$P.E. = \frac{e^2v^2}{2ma^2\omega^2}\left\{-1 - \cos 2\omega\,(t_o + \tau_1) + \cos(2\omega t_o + \omega\tau_1) + \cos\omega\tau_1 - \omega\tau_1\sin(2\omega t_o + \omega\tau_1) + \omega\tau_1\sin\omega\tau_1\right\}$$

Thus the energy taken from the deflecting system by one electron is

$$K.E. - P.E. = \frac{e^2v^2}{2ma^2\omega^2}\left\{2 - 2\cos\omega\tau_1 - \omega\tau_1\sin\omega\tau_1 - \frac{\cos 2\omega t_o}{2} + \frac{\cos 2\omega(t_o + \tau_1)}{2} + \omega\tau_1\sin(2\omega t_o + \omega\tau_1)\right\}$$

If the beam current is I, then the number of electrons emerging from the deflecting plates in time dt_o is $I dt_o/e$ and the power, P, consumed from the deflecting plates is

$$P = \frac{\omega I}{2\pi e}\int_o^{\frac{2\pi}{\omega}} (K.E. - P.E.)\,dt_o \qquad \cdots (11)$$

$$i.e., \quad P = \frac{I\,e\,v^2}{2ma^2\omega^2}\left\{2 - 2\cos\omega\tau_1 - \omega\tau_1\sin\omega\tau_1\right\}$$

but $P = \dfrac{v^2}{2R}$ and hence the input resistance is

$$R = \frac{ma^2\omega^2}{Ie}\left\{\frac{1}{2 - 2\cos\omega\tau_1 - \omega\tau_1\sin\omega\tau_1}\right\} \cdot \qquad \cdots (12)$$

A similar formula for the input resistance has been given by Hollman and Thomas [4, 9] but their method of derivation has been severely criticised by Gundlach, Bruche and Recknagel. [10, 11, 12, 13] However, the latter [12] has substantiated the formula by determining the induced current to the deflecting plates by using image theory and taking account of the fringing field. His method has the advantage that it also derives the reactive component of the input impedance, but it is felt that the above energy method is more fundamental and explains the actual mechanism of the input damping.

Colebrook[3] and Benham[7] have both given a formula for the input resistance which in the present notation is

$$R = \frac{ma^2\,\omega^2}{Ie}\left\{\frac{1}{1 - \cos\omega\tau_1}\right\}$$

This formula gives a finite value for R at zero frequency and is therefore incompatible with the physics of the problem. It can be obtained from equation (11) by omitting the potential energy or, in other words, by neglecting the energy returned by the electrons to the deflecting plates in the fringing field. It has been assumed above in deriving equation (12) that the electron's transit time in the fringing field is negligible compared with the high frequency period. Without this assumption it would be necessary to know the form of the fringing field. It seems preferable to take account of the fringing field with this assumption rather than to ignore it altogether.

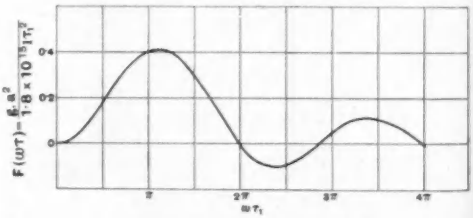

Fig. 7.—Variation of input conductance with transit angle in deflector space.

The input conductance can be obtained from equation (12) in the form

$$g = \frac{I\,e\,\tau_1^2}{ma^2}\;F(\omega\tau_1)$$

or in practical units

$$g = 1{\cdot}8 \times 10^{15} \cdot \frac{I\,\tau_1^2}{a^2}\;F(\omega\tau_1) \cdot \qquad \cdots (13)$$

where $F(\omega\tau_1) = \dfrac{2 - 2\cos\omega\tau_1 - \omega\tau_1\sin\omega\tau_1}{(\omega\tau_1)^2}$

When $\omega\tau_1$ is small so that powers higher than the second may be neglected, equation (13) reduces to

$$g = \frac{I\,e\,\omega^2\,\tau_1^4}{12\,ma^2}$$

Thus at zero frequency g is zero as is to be expected. At low frequencies g is proportional to the square of the frequency as in grid controlled valves. This applies for transit angles up to about quarter of a period. For larger transit angles g can be determined from equation (13) and fig. 7. It can be seen that

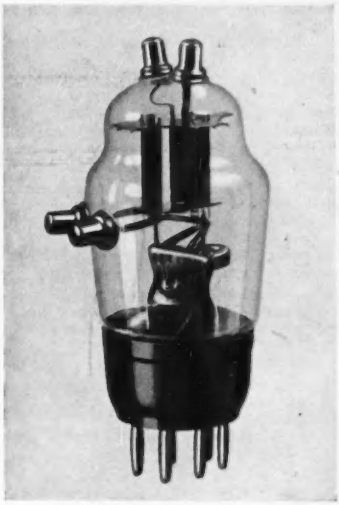

Fig. 8.—Deflected beam valve for 200 Mc/sec.

the damping has a maximum value for a transit angle of about π radians and that it has zero and negative values. In practice it is possible to make valves having a mutual conductance of a few milliamps per volt with R of the order of 10,000 ohms at $\omega\tau_1 = \pi$. Since R has its lowest value at this transit angle it is clear that in this respect deflection control has much advantage over grid control.

Examination of figs. 6 and 7 indicates that a transit angle of about 3π radians appears to be particularly promising.

5. PRACTICAL APPLICATIONS.

The above analysis shows that, on the grounds of sensitivity and input resistance, deflected beam valves show distinct promise for use at high frequencies and fig. 8 is an example of such a valve which has been designed for use with parallel wire transmission line circuits connected to the deflector plates and to the anodes through leads taken to four caps in the envelope.

The simple system shown in fig. 1 requires some elaboration to meet practical requirements and a cross section of the actual electrodes is shown in fig. 9. The current in the ribbon-shaped electron beam from the cathode C, is controlled by a grid, G, and focused by the electrodes A and B. The deflector plates are shaped in the manner shown to improve the focusing and a screen, S, with an aperture to admit the beam, is provided between the anodes, E, and deflectors, D, to screen the input from the output. A suppressor plate, P, is provided between the anodes to prevent secondary electrons flowing from one anode to the other, thus maintaining high output A.C. resistance.

The design of the suppressor is important. From the theoretical analysis given above it will be seen that the mutual conductance, both at low and high frequencies, depends on the width of the beam at the anode and the transit angles in the various parts of the valve. These two factors are not, however, entirely independent since both are determined by the electrode voltages. Over a wide range of

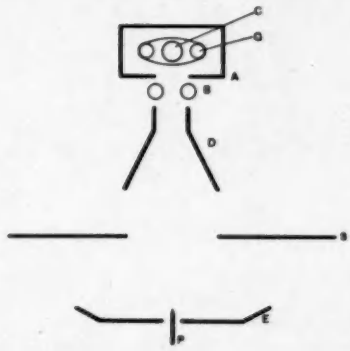

Fig. 9.—Cross-section of typical beam deflection valve.

operating conditions it is more important to ensure sharp focusing than large transit angles. With a very sharply focused beam, however, it is found that the suppressor plate reflects electrons which can travel back to the cathode where they add to the negative space charge and reduce the cathode current. The effect is most pronounced when the beam is in its undeflected position and when therefore maximum mutual conductance should occur. The effect can be minimised, but not entirely eliminated by giving the front of the suppressor a sharp edge and by ensuring that this edge does not project in front of the anode by more than is necessary to suppress the secondaries.

Valves of this type operate satisfactorily with the deflectors and anodes at mean potentials of 20 and 400 volts respectively, the mutual conductance being about 1 mA/volt at a total cathode current of 6 mA. The input resistance at 200 Mc/s is between 15,000 and 20,000 ohms and the gain per stage at this frequency is approximately 13 db. Although the cathode current is spaee charge limited, however, the shot noise of the anode current is high as the result of splitting the sharply focused beam between the two anodes and also due to effects in the beam itself. The signal/noise performance of the valves is, in fact, no better than that of pentodes. Deflected beam valves have also been developed for still higher frequencies up to 750 Mc/s. Some of these have a mutual conductance of 5 mA/V at 4 mA cathode current and considerable power gain can be obtained. However, as small signal amplifiers where noise is the ultimate limit to sensitivity these valves cannot compete with the modern space charge control valves in which the shot noise can be reduced by an amount which more than compensates for their lower input resistance.

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12. A. Recknagel, *Zeitschrift fur Technische Physik*, *Vol.* 19, *p.* 74, 1938.
13. A. Recknagel, *Ibid.*, *Vol.* 19, *p.* 616, 1938.
13. L. Malter, *R.C.A. Review*, *Vol.* 5, p. 439, April 1941.
15. D. Gabor, *Wireless Engineer*, *Vol.* 21, *p.* 115, March 1944.
16. J. H. O Harries, *Ibid.*, *Vol.* 21, *p.* 176, April 1944, and subsequent correspondence, *Gabor*, *Harries*, *Rodda*, *Benham*, June—December 1944.

A New Type of Supervisory Control System.

By N. C. SMART,

G.E.C. Telephone Works.

PREVIOUS articles in this Journal* have described supervisory control systems where the number of wires connecting control station to controlled substation was independent of the number of operations to be performed. Systems have been supplied using two or four wires and even, by the use of carrier current signalling, dispensing with pilot wires altogether. The purpose of this article is to describe a system of remote control which is radically different, in that the number of pilot wires is dependent on the number of operations to be performed, and is thus more allied to the type of remote control system normally used in, say, the control of switchgear in a generating station from a control room in the same or an adjacent building. It differs, however, from such systems in that the number of pilot wires is considerably reduced and low-voltage supply and telephone-type components are used throughout, as in the normal supervisory control system.

In designing this system, the object was to escape from the necessity of providing the relatively complicated selection equipment usually employed in supervisory control schemes. The following advantages are thereby gained :—

(*a*) Increased speed of operation.
(*b*) Less maintenance required.
(*c*) Lower cost.
(*d*) The absence of equipment common to the whole system but on whose satisfactory operation the system depends.

The disadvantage is, of course, that more pilot wires are required.

Neither the advantages nor the disadvantage should be exaggerated. Increased speed of operation is very often of little or no value. Modern supervisory systems can select and start to operate any one out of 100 circuit breakers in a time as short as 2 seconds. But

* *G.E.C. Journal*, Vol. II, No. 3, November, 1931, p. 146. Vol. IV, No. 3, August, 1933, p. 165. Vol. V, Nos. 2 and 4, May and November, 1934, pp. 115 and 234

this, in general, can only be achieved by more complex selection equipment. With regard to maintenance, it has been found as a result of some twenty years' experience of such systems that the amount of maintenance required is in no way excessive, although it cannot be denied that all such systems depend on the correct functioning of a rather complex piece of common selection apparatus. If this

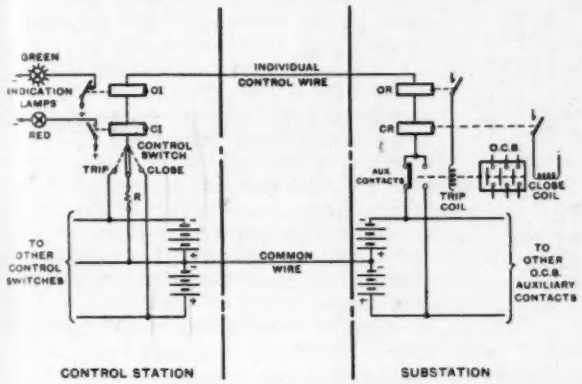

Fig. 1.—Fundamental supervisory control circuit using one pilot wire per circuit breaker.

is properly maintained it will give admirable service, but its failure means the loss of control over the whole substation. On the other hand, the disadvantage and extra cost of providing a larger number of pilot wires may in some cases not prove excessive. If the distance is short and the ground has to be opened in any case, say to lay the power supply cable, it may cost very little extra to provide, say, 20 cores instead of 2. But if the distance is great or the number of operations to be carried out excessive, and the ground has not otherwise to be opened, as for example when the power supply is overhead, then a normal supervisory control system is clearly called for.

To emphasise the above, two cases may be quoted where the type of system under consideration has proved more advantageous than the normal type. In the first case a small trolley-bus substation consisting of a mercury-arc rectifier, its transformer oil circuit breaker and two feeder breakers were required to be controlled. It was found that four cores were available in a pilot cable running past the site of the substation. By using a control system of this type it was possible to control each breaker and obtain continuous back-indication of its condition over one pilot wire, using the fourth core as a common return. In the second case a large group of switchgear had to be installed in a generating station at a considerable distance from the control gallery from which it had to be controlled. Further, the cable-run between these two points was very difficult and the space available on the gallery for the control panel was very restricted. The present type of system using a telephone-type pilot cable and a miniature control panel enabled both these difficulties to be overcome. It will be seen that in the first case this type of system was used in preference to a normal supervisory control system and in the second case in preference to a normal direct multi-pilot wire remote control system.

In general the basis of the system is the provision of one pilot wire for the control and back-indication of each circuit breaker. The basic circuit is shown in fig. 1. As will be described later, the circuit is capable of many variations in detail to suit particular cases, but all operate on the same principle. Two polarised telephone-type relays OI and CI ("open indicate" and "close indicate") are connected in series with the individual control wire at the control station via the resistance R to the mid-point of the 50-volt battery, which point is connected via one common wire to the mid-point of the substation battery. This battery is connected to the auxiliary contacts of all circuit breakers and so via the two polarised relays OR and CR to the other end of the individual control wire. Thus, in the condition shown, current flows from centre point of the substation battery over the common wire, resistance R, normal contacts of the control switch, relays OI and CI, individual control wire, relays OR and CR, auxiliary contacts of the circuit breaker, to the negative pole of the substation battery. The direction of this current and the polarisation of the relays are such that only relays OI and CR could operate. The setting of these relays is such, however, that only relay OI is operated, relay CR being so designed that it requires some four times this current to operate. When the breaker is in the closed position, conditions are similar except that the auxiliary contacts now connect the opposite pole of the substation battery to the relays

and so cause relay CI at control to operate. Thus, relays OI and CI indicate continuously and immediately the condition of the distant breaker. Contacts of these relays control the red and green indicating lamps on the control panel.

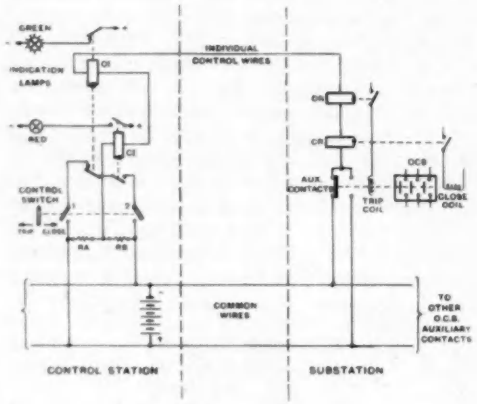

Fig. 2.—Modified circuit requiring battery at control station only.

When it is desired to close the breaker, the control switch is moved to the "close" position. This connects the positive pole of the control station battery to relays CI and OI and so over the individual control wire and relays OR and CR to the negative pole of the substation battery. The two half-batteries combine, and this, together with the absence of resistance R, increases the current through relay CR sufficiently to cause it to operate. Contacts of CR close the operating coil circuit of the breaker, via interposing relays if necessary, and so close the breaker. When the auxiliary contacts change over to the closed position they disconnect the negative pole of the battery and connect the positive pole. The control and substation batteries are therefore now in opposition, and no current flows in the line. Relays OI and CR release, extinguishing the green lamp on the control panel and opening the breaker closing coil circuit at the substation. This indicates to the control operator that the breaker has closed and he then releases the control switch, which returns to normal. The circuit for relay CI from the positive pole of the substation battery is thus completed and the relay operates, lighting the red lamp.

The following points are worthy of special notice:—

(1) It is not necessary to keep the batteries at control and substation at the same potential.

(2) Should an auxiliary contact fail an immediate indication is given by the extinguishing of both lamps.

(3) It is impossible to cause any operation of the breaker by short circuits or other faults in the cable.

(4) Disconnections in the cable are immediately indicated by the extinguishing of both lamps associated with the faulty core.

(5) The changing over of the relays on the occasion of a trip operation under fault conditions at the substation can be made to give audible and visual alarm signals.

There are two minor disadvantages in this system, one being that the two halves of the substation battery are likely to be unequally loaded, calling for separate charging of the two halves, and the other, that the sequence of lamp indications on the control panel when carrying out an operation is unusual in that the red lamp does not glow until the control switch is released.

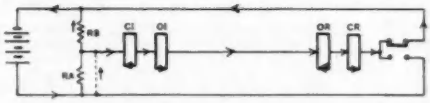

Fig. 2a.—Circuit conditions when breaker is being closed.

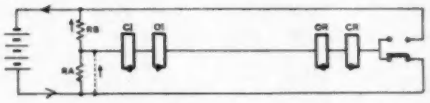

Fig. 2b.—Circuit conditions when breaker has closed.

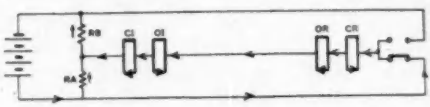

Fig. 2c.—Circuit conditions when relay OI has released.

It may also be objected that the battery responsible for providing the indications—virtually the only common piece of equipment—is located at the remote point. These difficulties have been overcome in the modified system shown in fig. 2. In this only one battery is provided and that is at the control station. Instead of being centre-tapped, it has two high resistances in series connected across it and the centre point of these resistances is brought out to form a neutral point. The positive and negative poles of the battery are connected by two common wires to the

substation. With the breaker open as shown in fig. 2, the current flow is from positive, resistance RA, relays CI and OI, individual control wires, relays OR and CR, auxiliary contacts of the breaker, common wire to negative. Fig. 2a shows this circuit in diagrammatic form. The value of the current is such that neither OR nor CR will operate and the direction is such that relay OI is operated, lighting the green lamp.

When it is required to close the breaker, the control switch is moved to the "close" position, thus closing contacts No. 1. Relay OI being operated, its contacts and contacts No. 1 short-circuit resistance RA, as indicated diagrammatically by the dotted line in fig. 2a. The four relays are thus connected across the whole battery without series resistance other than the line wire resistance. This increased current is sufficient to operate relay CR but, as the direction remains unchanged, relay OI remains operated. Contacts of relay CR operate the breaker, if necessary via an interposing contactor. When the breaker is closed the auxiliary contacts will move to the opposite side and so short out all four relays as shown in fig. 2b. Relay OI will release and at its contacts remove the short from resistance RA even though the control switch is still held in the "close" position. Conditions are thus as shown in fig. 2c, relay CI operating and so extinguishing the green lamp and lighting the red lamp to indicate that the breaker has closed. The control switch can now be returned to the normal position.

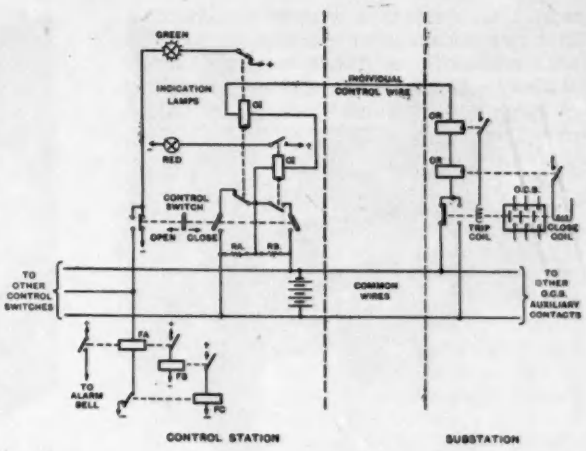

Fig. 4.—Supervisory control circuit with flashing lamp trip alarm.

It will be seen that at the expense of one further common line wire to the substation, the difficulties described above have been overcome. The only battery required is at the control point and it is not centre-tapped. The sequence of lamp indications is perfectly normal.

Where it is desired to provide a trip alarm using an amber lamp per circuit breaker and a common audible alarm, the modified circuit shown in fig. 3 may be used. This makes use of a type of control switch, which when operated to the "close" position makes a pair of auxiliary contacts, which remain closed when the control handle is returned to normal and can only be reset by momentarily turning the handle to the "open" position. An extra contact of OI is provided which, when closed, completes the circuit of the amber trip lamp via the auxiliary contacts of the control switch and a common alarm relay.

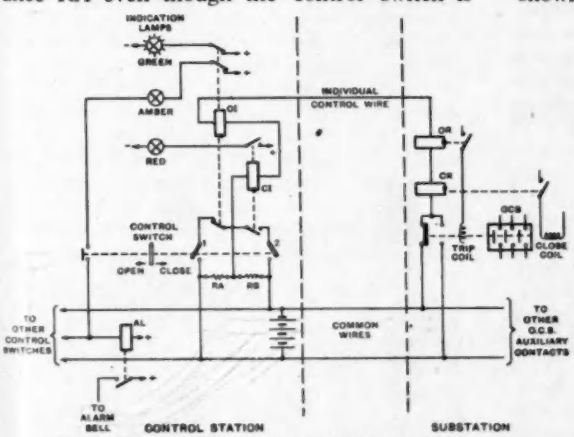

Fig. 3.—Supervisory control circuit with amber trip lamp.

While the use of an amber lamp to give a trip alarm is still regarded as standard practice, a new method is gaining favour. This was popularised by supervisory control systems and consists in flickering the indication lamp affected by a change. Thus, when a breaker trips out on fault, the red lamp is extinguished and the green lamp flickers until reset by a manual operation of the

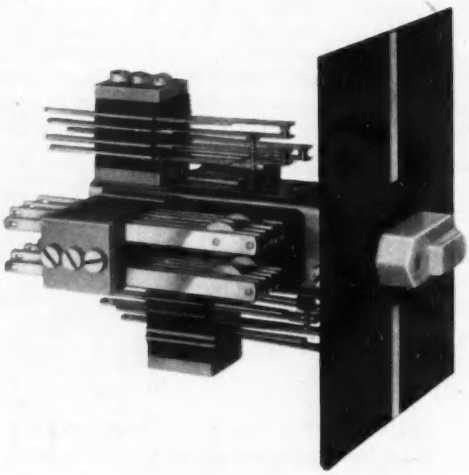

Fig. 5.—Control switch with illuminated handle shown in "open indicate" position.

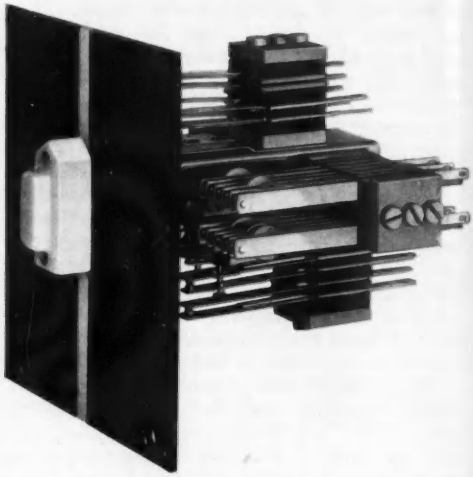

Fig. 6.—Control switch with illuminated handle shown in "close indicate" position.

control switch. The circuit of fig. 3 can readily be modified to give this facility, which can be provided by three telephone-type relays so interconnected that they pulse continuously at any desired speed, usually about one cycle per second. Fig. 4 indicates such an arrangement.

A new control switch has been developed specifically for use with such systems, although it has much wider applications in all forms of supervisory control and direct control. This is a miniature key with an illuminated handle which enables the usual red and green lamps to be dispensed with and which provides a continuous indication in a mimic diagram of the condition of all controlled or indicated switchgear. It may be of interest to indicate how this control switch can be adapted to the type of control system under consideration.

The switch is shown in figs. 5 and 6. It consists of a hollow rectangular base on the four surfaces of which are mounted contact spring assemblies of the telephone relay type or, where necessary, a more robust type capable of handling much heavier currents and higher voltages.

The spring assemblies are operated by a rotatable camshaft which passes through the hollow frame, and carries at its upper extremity a translucent hollow plastic moulded handle. Within this handle, and rotating with it, are two indication lamps connected in parallel. A substantial retaining spring can be arranged to hold the shaft in any one of four positions,

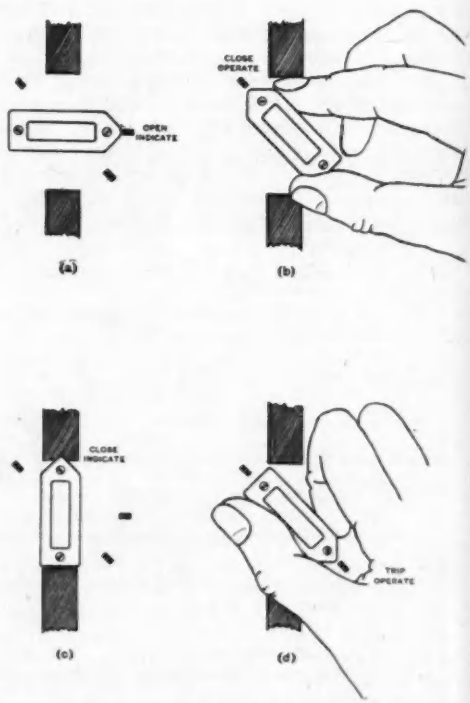

Fig. 7.—Illuminated handle control switch
(a) in "open indicate" position.
(b) held in "close operate" position.
(c) in "close indicate" position.
(d) held in "trip operate" position.

or alternatively the shaft can be arranged to stay in any particular position only so long as the handle is held in that position. By suitable arrangements of cams and springs a very large number of combinations is possible.

Fig. 7 indicates diagrammatically one arrangement which is suitable for use in control systems of the type under discussion. In the position shown at "a" the key handle is held by the restraining spring and the lamps are not lit. This indicates that the associated breaker is in the open position. When it is required to close the breaker the key is rotated counter-clockwise to the "close operate" position as shown at "b." In this position the switch is not held by the restrain-spring but will, on release, immediately fly back to the "close indicate" position as shown at "c." In either of these positions the lamp circuit is such that while the breaker is open the lamps in the handle will flicker. When in the "close operate" position, conditions are applied to the pilot wire as will afterwards be described, to cause the breaker to close. When the auxiliary contacts change over, conditions are applied to the pilot wire to cause the handle lamps to change from flicker to steady glow. The handle can now be released and will thereupon return to the "close indicate" position, and, provided that the breaker remains closed, the lamps in the handle will be extinguished. To trip the breaker the operations are similar. The handle is rotated to the trip operate position as shown at "d," the lamps flicker until the breaker trips when they glow steadily, the handle is released and flies back to the "open indicate" position, and the lamps are extinguished. With the breaker in the closed position and the handle in the "closed indicate" position, should the breaker be tripped by any cause other than a control operation, the lamps in the handle will flicker and the alarm bell sound. The handle is thereupon turned to the "open indicate" position; the lamps are extinguished and the alarm ceases.

It will be seen that in general terms the lamps are only extinguished when the handle is in the indicate position agreeing with the present condition of the associated breaker. The lamps flickering indicate that the handle disagrees with the breaker, and glowing steadily indicate that the selected operation has been successfully carried out. As the handle is arranged either to complete the mimic diagram line or interrupt it, a very clear indication is given of the state of the switchgear under control. As the two lamps are connected in parallel there is no danger of false indication due to lamps burning out.

As this control switch is of small frontal area, approximately 2in. by 2in., it is possible to arrange a mimic diagram control panel in a very restricted space while still retaining an extremely clear diagram layout. As an indication of this, fig. 8 shows a suggested layout of a control panel for a rectifier substation having two incoming E.H.T. oil circuit breakers, one rectifier transformer oil circuit breaker and three D.C. feeder breakers all controlled and back-indicated, using this illuminated handle control switch. Fig. 8 is shown half full size and indicates that a substation of this size requires an area of approximately one-third of a square foot of control panel space.

Fig. 9 shows a circuit which, while basically the same as fig. 2, has been specially designed

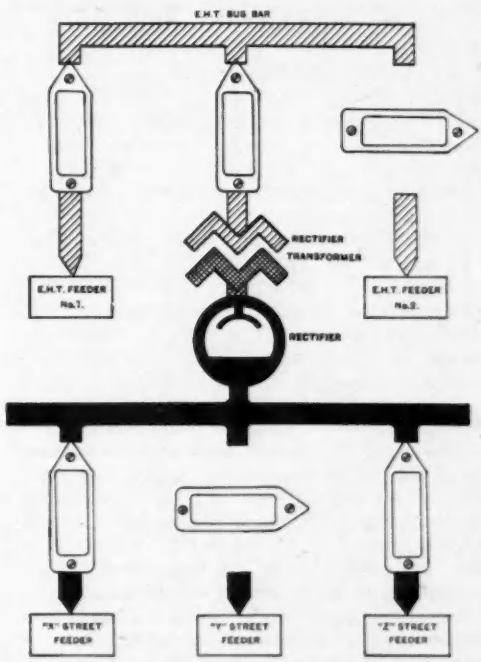

Fig. 8.—Control panel, using illuminated handle control switch, shown half actual size.

to work with this illuminated handle control switch.

In the position shown the breaker is closed and the switch handle is in the "close indicate" position. Current flow is from positive pole of the battery over one of the common wires

to the substation, the auxiliary contacts of the breaker, relays CR and OR, individual control wire, relays OI and CI, resistance RB to negative. The current direction and strength is then such that only relay CI is operated as shown. It will be seen that there is no circuit for the lamps in the control switch handle, or for the common alarm. Now if the circuit breaker trips for any reason other than a control operation, when the auxiliary contacts change over the direction of this current is reversed and relay CI will release and relay OI operate. A circuit is thus completed from positive via the two handle lamps in parallel, the "close indicate" contacts of the control switch, the operated contacts OI2, common flicker relay FA, to negative at contacts of FC. The flicker relays operate and so cause the lamps to glow intermittently, and the audible alarm sounds. This continues until the handle is rotated to the "open indicate" position when the circuit described above is broken by the opening of the "close indicate" contacts. The lamps are extinguished and the alarm ceases.

Starting again with the breaker closed and the control switch in the "close indicate" position, when it is desired to trip the breaker the handle is first rotated to the "open indicate" position and then through a further 45 degrees to the "trip operate" position as shown in fig. 7d. Both "open indicate" and "trip operate" contacts will now be closed. The first completes a circuit via operated contacts CI2 to cause the lamps to flicker. No. 2 "trip operate" contact completes a circuit via operated contacts CI1 to short-circuit resistance RB, thus increasing the current in the relay circuit to a value sufficient to cause relay OR to operate and so trip the breaker. When the auxiliary contacts change over to the open position, current in the relay circuit falls to zero and so releases relay CI. Released contacts CI1 remove the short-circuit from resistance RB, and so cause a current of the opposite polarity and low value to flow again in the relay circuit (see fig. 2). Relay OI therefore operates. When relay CI released a circuit was established from negative via No. 1 "trip operate" contact, released contacts CI2, "open indicate" contact, handle lamps, to

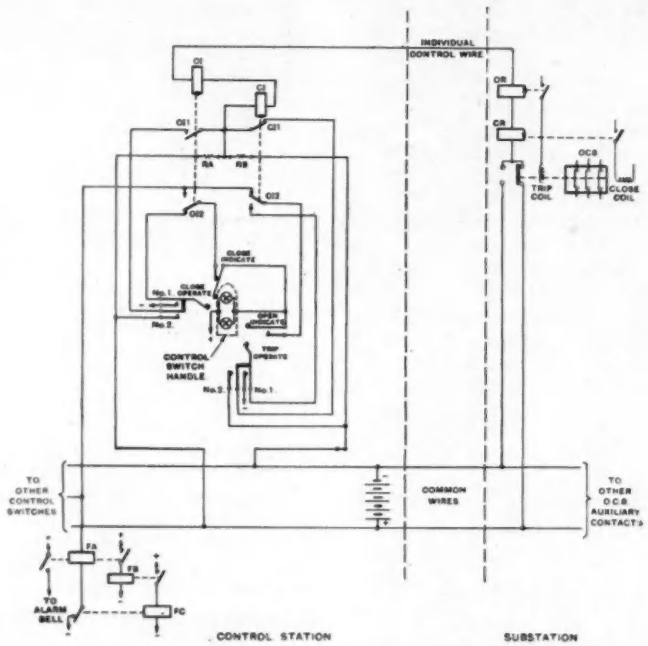

Fig. 9.—Supervisory control circuit using illuminated handle control switch.

positive. The lamps therefore glow continuously, indicating that the operation has been successfully carried out. The handle is then released and flies back to the "open indicate" position. This opens the two "trip operate" contacts and breaking the lamp circuit detailed above, causes the lamps to be extinguished. The operation of closing the breaker is similar.

From the above it will be seen that the basic circuit described, or one of its derivatives, is capable of providing a simple, reliable and compact control system where the number of wires available from control to controlled point is substantially equal to the number of breakers to be controlled. The apparatus used is simple and reliable and any desired type of control switch may be used although it is considered that the illuminated handle type will give the clearest indications, simplest operation and require smallest control panel space. It should again be pointed out that this system is in no way competitive with the usual supervisory control system except, as mentioned above, when the required number of control wires is available.

The Protection of Lighting Fittings against Weathering and Corrosion.

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G.E.C. Research Laboratories.

INTRODUCTION.

IN the period preceding the war it was estimated that not less than forty million pounds were spent annually in this country on the protection of iron and steel structures and equipment against rusting[1]. The problem is acute in all branches of engineering, and it is of special significance in the illuminating engineering field because of the need to maintain reflecting efficiency as well as mechanical strength and appearance.

The engineer must devise schemes to give adequate protection relative to the expected life of the fittings and to the maintenance facilities which are available.

Although much information is now available, the complexity of the problem is so great that we are still far from being able to give a final answer in the form of fittings wholly immune from corrosion in all locations. It is possible, however, to make fittings having a satisfactory service life and performance in known conditions.

1. THE NATURE OF ATMOSPHERIC CORROSION.

The process of corrosion involves many factors associated with both the materials used in the equipment and the corrosive media, and the interdependent relationships between these many factors. It has been suggested that the complexity of the subject allied to the limited amount of knowledge at present available make the formulation of any firm theory of corrosion impossible. Nevertheless good working theories have been established, on the basis of which the engineer can assess the relative importance of the various factors as they affect his particular problem.

It is convenient to consider the process under two main headings: the atmospheric corrosives which are responsible for the attack, and factors associated with the equipment which is subject to attack.

The Atmosphere as a Corrosive Medium.

The constitution of the atmosphere undergoes great and uncontrollable variations. Its corrosive properties not only vary widely from place to place, but are also constantly varying at any given place. It is not possible to analyse in detail these changes; what can be done is to study the effect of different constituents of the atmosphere on the corrosion process and the frequency of their occurrence in different broad groupings of location.

Lighting fittings have to operate both outdoors and indoors. In many industrial

situations special problems are created by the presence of chemical fumes[2], but these are not considered in the present article; the atmospheric factors dealt with are those which are widespread and common to the majority of locations.

The corrosives of the atmosphere may be divided into three main groups: (1) The gases present in the atmosphere; (2) Moisture; and (3) Solid particles.

(1) Of the atmospheric gases which are active in corrosion, oxygen and carbon dioxide are present universally and in reasonably constant concentrations. The importance of oxygen is sometimes overlooked; for example the high resistance of pure aluminium to atmospheric attack is due to the formation of a very thin, tightly adhering film of oxide over its surface. It is important, too, in relation to the action of other corrosives such as sulphur dioxide.

Oxygen, carbon dioxide and sulphur dioxide are the most widespread corrosive gases. They are readily absorbed by contact with solid surfaces and so are most concentrated in the immediate region of their sources, which are usually towns.

(2) The importance of moisture in the corrosion of lighting fittings has been repeatedly demonstrated. Anodised aluminium reflectors which were unaffected after six months' exposure in the highly sulphurous, but dry, atmosphere of a magnesium alloy foundry, were rapidly attacked when exposed out of doors in a mild suburban atmosphere.

The moisture content of the atmosphere shows itself both in the general humidity and in condensation, as in the formation of dew, fog, and rain. There is a tendency to neglect the importance of moisture in the corrosion process, except where condensation takes place, but it can play an important part at relative humidities less than 100 per cent. Solids, and in particular corrosion products, are able to absorb moisture at humidities above a critical value peculiar to the solid, and the amount of corrosion may be proportional, in some reactions, to the time the humidity lies above the critical value. Humidity values at any given location vary greatly, both seasonally and diurnally, and are affected by the prevailing wind.

Condensed moisture, and particularly rain are even more important than general humidity. As to whether the total rainfall is an important factor, there is some doubt. It is possible that the frequency, type, and duration of rainfall are at least as important as its total amount.

Nevertheless it would be unwise to conclude that fittings and equipment which are satisfactory in a relatively dry area of the country will be equally satisfactory in areas of greater rainfall.

(3) The solid particles present in the atmosphere affect both the progress of corrosion and the type of attack. Vernon[3] has shown that solid particles not only act as centres for the retention of moisture, but also as "poultices" which retain acute corrosion constituents other than moisture, *e.g.*, chlorides and sulphur dioxide. The action is thus localised so that pitting is more common in heavily polluted atmospheres than in clean locations. The presence of solid particles in the atmosphere also aids in fog formation which is conducive to corrosion attack.

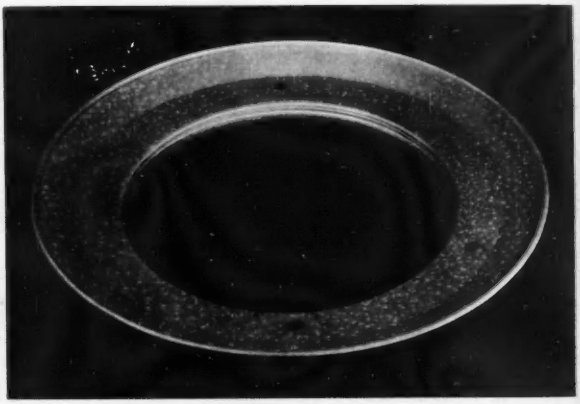

Fig. 1.—Anodised aluminium alloy street lighting reflector after three months' exposure.

Near to large towns the majority of the solid pollution comes from industrial smokes. In the region of the sea-coast, however, chlorides may be deposited and constitute possible centres of corrosion action. It is not often, however, that their influences extend more than 5—10 miles from the coast and their activity falls off rapidly at more than half a mile from the sea, although this depends on the prevailing wind. Where there is a mixture of chlorides and sulphur compounds, as in sea-side towns, it appears that the effect of the sulphur compounds tends to over-ride that of the chlorides. Their joint action,

however, has been shown by experience to be one of the most powerful with which the lighting engineer has to contend.

Generally speaking it is impracticable to vary the protective treatment of equipment according to the conditions in a particular area, and protective schemes must be adopted which will cope with the most severe locations in which the fitting is likely to operate.

Corrosion Properties of Materials.

The nature of the atmosphere can be regarded as the *cause* of any corrosion which may take place ; its constitution can be roughly determined but it cannot be controlled. Factors associated with the equipment will determine *whether* attack takes place ; a combination of factors associated with both the atmosphere and the design of the equipment will determine the extent and rate of any attack.

The glasses used in lighting equipment can be regarded as immune from atmospheric attack in the types of atmosphere in which fittings normally operate and for the life expected of them.

In contrast to the glasses, the paints used for protective and optical purposes have a relatively short life.[4] The setting process of most paints consists of oxidation and polymerisation which result in the production of a hard film. During life this film undergoes slow changes, which are accelerated by heating. As the film hardens, changes naturally take place in its other physical properties ; important among these changes is a decrease in adhesion and a diminution in flexibility. A new film, being flexible, can adjust itself to changes due to expansion and contraction of the surface to which it is applied, but as the film ages and hardens it can no longer follow these changes and tends to split and peel away. In addition to failure through hardening, the film may break down, or lose its adhesion due to penetration by moisture.

It is, however, with the corrosion of metals that the illuminating engineer is primarily concerned and it is important to appreciate the main types of metallic corrosion which may occur.

The most fundamental type is direct chemical action between a single metal and the corrosive media of the atmosphere. In its simplest form this results in comparatively uniform attack over the whole surface, but in practice this simple action is usually modified by localised corrosion superimposed on the general action.

Such localised corrosion, evident as "pitting," is one of the most familiar forms of corrosion and is illustrated in fig. 1, which shows an anodised aluminium alloy reflector after exposure out-of-doors. It is very likely to occur when small areas of a surface are exposed to repeated attack, as when an anodic surface breaks down or when a paint film is porous, but it is also characteristic of other types of corrosion attack such as some forms of galvanic action.

Of all the forms of corrosion, galvanic corrosion, occurring when dissimilar metals are connected together under corrosive conditions, is probably the most widely appreciated. In the construction of many lighting fittings unprotected junctions of dissimilar metals are frequently exposed to the atmosphere and the probability of attack at these junctions will then depend on the metals used.

The common metals and alloys have been arranged according to their tendency to

TABLE 1.

Relative susceptibility of metals to galvanic action.

Corroded end (anodic)	This series is built upon actual experience with corrosion and laboratory measurement. Metals grouped together have no strong tendency to produce galvanic corrosion on each other ; connecting two metals distant on the list from each other tends to corrode the one higher in the list. Voltage figures are not given because these vary with every new corrosive condition. Relative positions of metals change in many cases, but it is unusual for changes to occur across the spaces left blank. The chromium-irons and chromium-nickel-irons change position as indicated depending upon oxidising conditions, acidity, and chloride in solution. The series as it stands is correct for many common dilute water solutions, such as sea water, weak acids and alkalies.
Magnesium	
Aluminium	
Duralumin	
Zinc	
Cadmium	
Iron	
Chromium-Iron (active)	
Chromium-Nickel-Iron (active)	
Soft Solder	
Tin	
Lead	
Nickel	
Brasses	
Bronzes	
Copper-Nickel Alloys	
Copper	
Chromium-Iron (passive)	
Chromium-Nickel-Iron (passive)	
Silver Solder	
Silver	
Gold	
Platinum	
Protected end (cathodic)	

corrode galvanically in the order shown in Table I by McKay and Worthington.[5] This is not an "Electro-Chemical Series," but due to the fundamental chemical affinities, it has some general analogies with the "Electro-Chemical Series."

Action will occur only when the corrosive conditions are such as to set up a galvanic current and this usually means the presence of moisture. If the unprotected junctions of dissimilar metals can be kept dry, it is unlikely that galvanic corrosion will take place. It is, however, easy to over-emphasize the importance of galvanic corrosion in the choice of materials; other factors, such as mechanical strength, may override corrosion considerations.

In the purely galvanic action a potential difference is developed between two different metals in a common electrolyte, but a potential difference can also be developed by a single metal in different electrolytes or in different concentrations of the same electrolyte.

Some lighting fittings (street lighting lanterns mounted on trolley-bus poles, for example) are subjected to dynamic stresses. If the fittings operate in a corrosive atmosphere these stresses may give rise to "corrosion fatigue." The surface of the metal is frequently the place where the mechanical stress is greatest and it is at the surface of the metal that corrosion commences. When the metal surface corrodes its fatigue resistance falls; the fatigue stresses themselves accelerate corrosion, so that the two actions supplement each other. This results in deep, steep cracks being formed which lead eventually to fracture. The effect of mechanical stress is apparently to change the *distribution* of corrosion rather than its magnitude, causing the attack to be concentrated at points of high stress. Static stresses in materials may also give rise to corrosion, particularly with brasses, some types of stainless steel, certain types of aluminium alloys and lead. The surface condition of the metals also has some influence on the corrosion process and particularly on its initiation; for example, surface irregularities may weaken a protective film at isolated points.

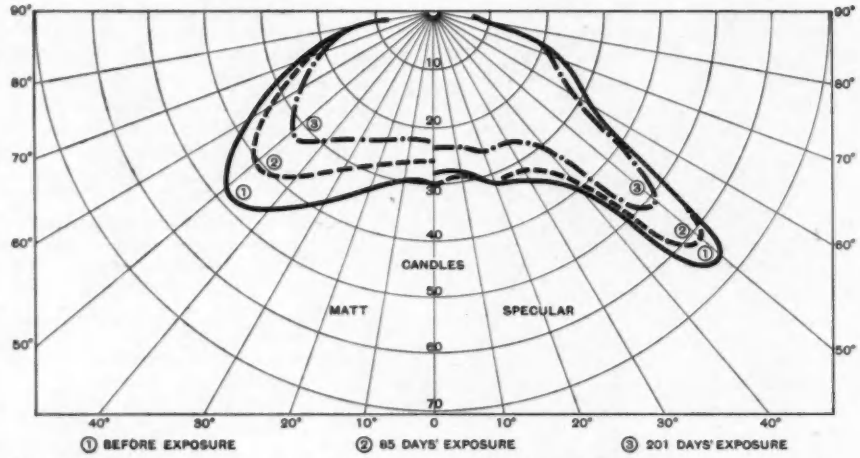

Fig. 2.—Light distribution of specular and matt anodised aluminium reflectors exposed at Euston Station. (1) Before exposure. (2) 85 days' exposure. (3) 201 days' exposure.

One other factor which may influence the corrosion process is the temperature at which the different parts of the fitting operate. Corrosion reactions are generally sensitive to temperature changes, increase of temperature frequently accelerating the rate of attack.

2. THE PROTECTION OF LIGHTING FITTINGS.

There are four main lines of defence against corrosion attack on lighting fittings: (1) Choice of materials; (2) Mechanical design; (3) Finishing processes; (4) Maintenance. The protection of both the optical surfaces and mechanical components of fittings has to be considered.

Choice of Materials.

Optical surfaces.

The curves of fig. 2 show the light distribution given by a small aluminium re-

flector before and after exposure in a heavily polluted industrial atmosphere, the reflector being cleaned before the curves were taken. Not only has the light output fallen through deterioration of the reflector surface, but the form of distribution has changed. It is essential that the light control exercised by the optical surfaces of a fitting shall not seriously alter during the life of the fitting. It is also desirable that the appearance shall not suffer unduly; performance of the reflector shown in fig. 1 is not seriously affected by the pitting but its appearance would not be acceptable.

No serious corrosion problem arises where light control is exercised by refraction or by transmitted diffusion. Glasses used for these types of control can be regarded as permanent in properties for the period of the life of lighting fittings in all ordinary atmospheres. Some plastics are beginning to compete with glasses for certain forms of diffusing and refracting equipment, and it seems that they also have very good weathering properties, although more service data are needed before their performance can be fully assessed.

Reflecting equipment, and particularly specular reflectors, offer more complex problems. This is due in part to the use of a greater range of materials, most of which are composite in character, such as silvered glass and rhodium-plated brass.

The most generally used specular reflector is back-silvered glass. Since the glass can be regarded as impervious to attack, deterioration will take place through the backing or at the edges of the glassware, and results in the destruction or peeling of the silvering. For general indoor use where the reflector operates in dry atmospheres, as, for example, in shop window reflectors, a finish of adequate durability has been obtained by following the silver plating with a heavy deposit of electro-plated copper, and finishing with aluminium paint. In exposed outdoor locations a more satisfactory backing is electroplated lead; the silvering of the reflectors is followed by a thin deposit of copper and a heavy deposit of lead. The two wing-type street lighting reflectors shown in fig. 3 illustrate the value of lead-backing; these reflectors were photographed after exposure at Blackpool in positions near to the sea front.

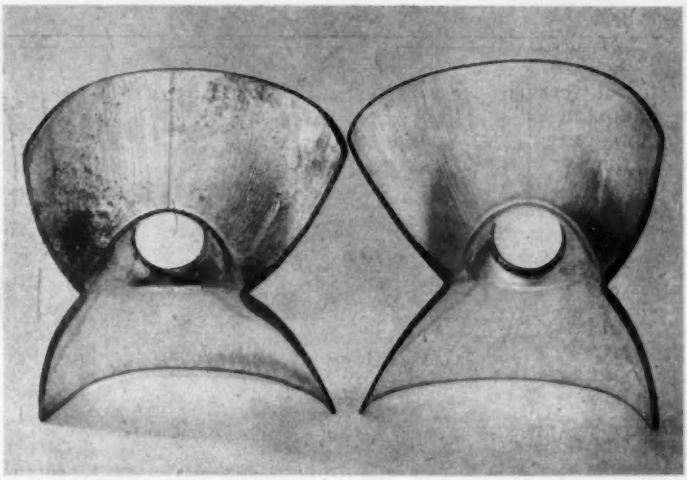

Fig. 3.—Exposure test on reflectors. Left-hand reflector—silvered, copper backed with aluminium paint finish (1 year exposure). Right-hand reflector—silvered, copper backed with electro-plated lead finish (2 years' exposure).

The chief alternative to silvered glass for use as a specular reflector is probably electrolytically brightened and anodised aluminium. Although its specular reflectivity is some 10 per cent lower than that of silvered glass, it possesses advantages in its low weight, ease of working, and resistance to breakage. Field tests made by the authors[6] showed that it was not suitable for use where the surface was liable to be wetted by rain or other condensed moisture. Under these conditions the anodic film was susceptible to attack showing either as a surface "bloom" or as pitting or both.

In dry situations anodised aluminium reflectors should have a satisfactory life performance.

Plated metals form another group of specularly reflecting materials which find use in lighting equipment. Plated finishes of chromium, rhodium and speculum metal have all been used for reflector surfaces.[7] They seem, however, to offer no general advantage over anodised aluminium as far as weathering is concerned.

At present lead-backed silvered glass is the most durable specular reflector, though the other materials discussed have sufficient resistance to weathering for use in the majority of indoor lighting equipment.

Diffuse reflectors can be divided into reflectors in which the active surface is enamelled or painted and those in which the reflecting medium is also the body of the reflector. The principal representatives of the second group are opal glass and pigmented plastics. Their use has been largely confined to interior equipment and for this their durability is wholly satisfactory.

Of the group comprising the paints and enamels, vitreous enamel is the most widely used finish. It has been proved by experience to be very resistant to almost all forms of atmospheric attack, provided that the surface can be guarded against chipping or cracking during transport and erection. Where mechanical damage to the vitreous surface makes it possible for corrosives to attack the base metal, however, failure is liable to be rapid.

The service performance of high temperature stoving paints examined to date is not so good as that of vitreous enamel even in indoor locations. This is due partly to the raised temperatures at which many reflecting surfaces have to work, and it is difficult to formulate a white paint which will stand temperatures of the order involved for prolonged periods without discoloration. The advent of paints having a higher heat resistance may change this position eventually. In indoor fittings working at lower temperatures, the rate of discoloration is less and the general performance of the finishes more satisfactory.

Housings and Mechanical Components.

In lighting equipment, such as diffusing fittings and industrial dispersive reflectors, the light controlling surfaces themselves form the major part of the fitting and the problem of providing a durable surface is largely that of achieving a mechanical construction sufficiently protected to withstand weathering. The designer of decorative fittings is, however, concerned about the maintenance of appearance, not only in the optical components, but also in the gallery and other metal work associated with the fitting. The appearance of surfaces having a high polish is very sensitive

Fig. 4.—Street lighting lantern with spun copper body.

to attack, a slight tarnish being sufficient to mar them. Chromium plate is used successfully provided that a good plating schedule has been followed.[8] This plating, though very resistant to tarnish, is porous, and reliance against corrosion attack is placed on the preplating of nickel. There are two comparatively new materials which should be useful to the designer. Speculum metal plating has been mentioned previously for use as a reflector surface; its greatest use may, however, be found as a finish for galleries and components. Resistance to tarnish in dry atmospheres is good and its appearance is rather more pleasant than that of chromium plating, being very similar to that of silver. The other new material is anodised aluminium. One of the most valuable properties of the anodic film is its ability to absorb dyes making available a material with a large range of

coloured finishes and with a high degree of permanence when used indoors. The aluminium surface can also be etched to give a satin finish.

A material that has proved to be of good service in the construction of some outdoor fittings and floodlights of the lighter type is lead coated sheet steel. The lead coating is on both sides and lends itself readily to soldered assembly. The fitting is painted before exposure.

Spun copper housings are used successfully in many exterior fittings and have the advantage of the high corrosion resistance associated with copper, brass and bronzes. Special surface treatments prior to painting are not needed and from a corrosion point of view these fittings have been proved satisfactory by experience.

Fig. 5.—Street lighting lantern with cast aluminium alloy body.

With the increased accuracy of light control resulting from the use of carefully designed refracting equipment in street lighting lanterns, it became necessary to adopt a more rigid form of construction than that offered by spinnings, and many lanterns now employ a casting for the main component of the housing. Figs. 4 and 5 show two modern street-lighting lanterns having spun and cast constructions. Good quality cast iron has found considerable use in some lighting equipment and provided that the right type of iron and the right painting schedule is specified the corrosion resistance is high.

The call for high rates of production with minimum machining of castings has led to the widespread use of die-cast aluminium alloys. The fittings designer has a number of aluminium alloys which will satisfy his requirements for strength, good casting properties, and reasonable cost, and his final choice will probably be determined by his attitude towards two alternative systems. He can select, on the grounds of cost, an alloy having a relatively low inherent corrosion resistance, and obtain the necessary weathering resistance by a fairly elaborate finishing schedule; or he can use an alloy having inherently good corrosion resistance but which will probably be more expensive initially, and simplify the finishing processes. Field tests and service experience suggest that the second process is usually to be preferred. It has the advantage that if the protective finishing breaks down, the extent of the corrosion attack will be limited and there will be little likelihood of serious trouble.

The metal to be used for the main body of the lantern having been decided, it is possible to choose those for the auxiliary components. Although these have been referred to as "auxiliary" components, this does not mean that they are of minor importance; severe corrosion attacks at points such as hinge-bolts or toggle-catches can easily result in the lantern becoming useless through inability to open it for servicing. Metals for components can be chosen which have an inherently high corrosion resistance, or which have the necessary mechanical properties but which have to depend on additional protective processes to obtain the necessary corrosion resistance. Chief among this second group are the mild steels which can be protected against rusting by such processes as galvanizing, electro-galvanizing and cadmium plating. A high degree of protection can be given to mild steel components by good galvanizing, using coatings of adequate thickness, freedom from porosity and good adhesion. The need for thick coatings has been shown by tests in which a zinc plate was exposed in an industrial atmosphere; after one year's exposure it had lost more than ·0003 in. in thickness. A thickness of ·004 in. should withstand any atmosphere for at least 10 years. Mild steel is an attractive material for many of the auxiliary components of lighting fittings, but unfortunately the high degree of corrosion resistance conferred on it by galvanizing is nullified by the low abrasion resistance of the zinc coating. In the course of maintenance many of these components suffer considerable mechanical wear and the galvanized coating is abraded relatively quickly allowing rusting to start. Fitments for the interiors of lanterns protected from rain can be made from mild steel which is either galvanized, or electro-galvanized and passivated.

Fig. 6.—Earlier pattern side entry DIFRACTOR lantern.

Design of Fittings.

The choice of materials from which a fitting will be made and the design of the fitting are obviously two parts of one problem. Much can be done to minimise the effects of corrosive attack by suitable mechanical design. It is almost impossible to exclude the corrosive gases from the vulnerable points of a fitting, but they are only dangerous when moisture, and to a lesser degree, solid pollution, are present. If important points of the equipment can be protected against these two, the probability and the rate of corrosion will be reduced.

Optical Surfaces.

The most obvious method of preventing both moisture and dirt from reaching the surfaces is to enclose them in a sealed construction such as the "sealed beam" motor car headlight popular in the United States. Some fittings are virtually air-tight and many modern street lighting lanterns are fitted with gaskets so that little "breathing" can take place. Wherever there is danger of direct atmospheric attack on a sensitive optical surface an enclosed construction is desirable.

Housings and Mechanical Components.

The housings of fittings will generally be subject to the full effects of atmospheric attack, but even so better service performance can be obtained by using constructions in which vulnerable points, such as hinges, are protected. As an example, we may consider the G.E.C. Difractor lantern which was first marketed in the form shown in fig. 6. Owing to war conditions, few of the installations received good maintenance, with the result that these lanterns were exposed for 5—6 years to a "forced service test." In some lanterns it was found that the spring ring refractor carrier had tended to seize in the hinge holes, so that in the new series of lanterns the holes have been packed with grease and a rather larger clearance allowed. One of the most interesting changes in design concerns the method of securing the lantern to the bracket arm, which was done in the pre-war model by two draw bolts passing through the lug of the casting and pulling up on to the arm when tightened in position. A few of these lanterns were installed on a very exposed part of the Scottish coast and no maintenance was done during the war. The corrosion attack was extremely severe and resulted in mechanical failure in a few instances; the cast ring from one of these lanterns is shown in fig. 7. It will be seen that fracture has taken place through the lug, the attack starting apparently at the drawbolts; if this was so, it may have been accentuated by corrosion fatigue since this is a point of high mechanical stress. In the new type lantern shown in fig. 8 not only is a different alloy used but fixing is achieved by Allen screws running through the thickened underside of the lug on to the bracket arm; the Allen screws are set in recessed holes which are packed with jointing compound after installation.

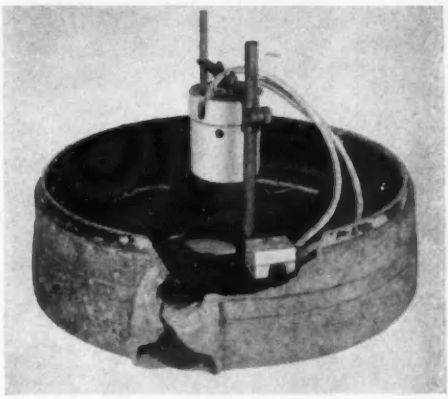

Fig. 7.—Corroded casting of earlier pattern side entry DIFRACTOR lantern.

Finishing.

We are largely dependent on the finishing processes, such as anodising and painting, for obtaining good corrosion resistance, particularly for equipment designed for outdoor use. This, of course, refers only to the protection of housings and other mechanical components; the application of protective finishes to optical surfaces has been discussed on pages 114, 115 and 116.

Really satisfactory finishing can only be obtained by treating the finishing process as an integral part of the design problem; for example, the pre-treatment and painting schedule for aluminium castings will be quite different from that which would be used with cast iron.

The finishing of fittings for operation in normal indoor atmospheres calls for little comment. Vitreous enamel and synthetic stoving paints have proved to be generally satisfactory. Possibly dyed anodised aluminium and plastics will find increasing use; their durability under these conditions is satisfactory.

Outdoor equipment, however, requires more careful consideration of the finishing schedule. Where aluminium alloys are used a good protection can be given by anodising. There are many different anodic processes and their value varies with the process. In industrial and marine atmospheres which

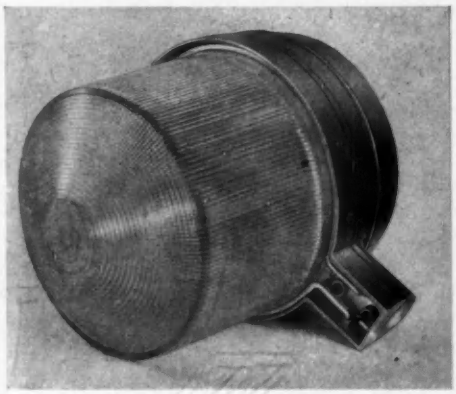

Fig. 8.—New pattern side entry DIFRACTOR lantern showing fixing by means of Allen screws.

produce marked corrosion of an unprotected aluminium-silicon-manganese-magnesium alloy in six months, corresponding specimens anodised by the sulphuric acid process show no signs of breakdown after 15 months' exposure (see fig.9).

Considerable work has been done on anti-corrosive paints. While the use of the wrong paint can cause rapid breakdown, failure also frequently results from poor cleaning and preparation of surfaces prior to painting. Thorough cleaning and degreasing should always be carried out. Paints protect a metal surface in two ways: first, by covering the surface with a water-excluding film of oil or

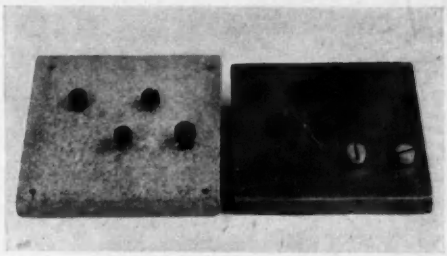

Fig. 9.—Exposure test on cast slabs.
Left-hand side—6 months' exposure on unanodised sample.
Right-hand side—15 months' exposure on anodised sample.

oil-resin, and secondly, by applying a corrosion inhibiting pigment to the surface, the pigment being embodied in the medium of the paint. To get good adhesion of the paint it is customary to process the metal surface. Anodising may be used for aluminium, but it is not always essential and there are several simpler and cheaper processes available that give adhesion of the same order. For mild steel, treatments of the phosphate type are effective, and recent development work by Hedges and Jordan[9] has shown that an extremely thin coating of tin on steel greatly improves the adhesion of paint and the corrosion resistance of the painted specimen. When the requirement of good adhesion has been satisfied the next important requirement of the paint film is that it shall be as impermeable as possible to water. Not only must the film be as water resistant as possible; there may be water soluble impurities in the paint, or the pigment itself may be liable to absorb water, and care must be taken that the pigmentation of the paint will itself effectively obstruct water seepage. Graphite and aluminium powder have leafing properties which help to this end. All of these requirements can be met by modern paints. The present tendency in G.E.C. street-lighting equipment is to use an aluminium pigmented paint for finishing, though black finishes have also proved successful. There is one other requirement

which the painting system must satisfy: the finishing coat must be of such a type that when repainting becomes necessary it will key well with such specified air drying paints as may be used for maintenance purposes. One other type of finish worthy of mention is metal spraying, which is particularly applicable to iron and steel. Steel plates sprayed with aluminium to a thickness of ·003 in.—·006 in. showed no sign of rusting in 4—6 years' exposure, while zinc sprayed iron has given good results.

Maintenance.

When all of these precautions in manufacture have been taken, the fact remains that much of the responsibility for satisfactory performance depends on adequate maintenance.

Painted surfaces should be repainted before breakdown of the top coating commences. This enables the existing film to be used after rubbing down as a satisfactory surface for the new coat. It is always advisable to use an air-drying paint which has been specially formulated to bond to the original top coat. Trouble at moving joints can be largely overcome by periodic greasing. In a complicated fitting such as a street lighting lantern, corrosion is bound to set in if maintenance is neglected.

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